Batteries, Battery Management, and Battery Charging Technology

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Article Outline

Glossary

Alternating current (AC) Usually in the form of a sine wave, the bidirectional current flow continually reverses. Typically, AC will have a zero mean (average) and a nonzero RMS value. In the USA, most "grid" electricity is generated and distributed in the form of 60 Hz sinusoidal waveform. In other areas of the world, 50 Hz is commonly used.

Amp-hour (Ah) A unit of electric charge, the amount of current delivered for 1 hour.

Battery A group of one or more cells electrically connected in series and/or parallel combinations to achieve higher voltage or current than what is capable from a single cell.

Battery management system (BMS) An electronic device or system that monitors and controls a rechargeable battery. Parameters measured may include cell temperature, voltage, and current. From this data, the BMS can compute the state of charge of the battery and estimate the state of health, remaining cycle lives, or remaining service life. Typically, a BMS system will include the ability to communicate with a host system and battery charger. The BMS may also contain sensors and circuitry for protection such as over-current, over-temperature, or over-voltage.

Battery pack A group of batteries or individual cells electrically connected in series and/or parallel combinations along with the required electrical interconnections, mechanical packaging, thermal management, and sensing circuitry. Because it is a self-contained assembly, a battery pack can be easily swapped in and out of the application.

Battery string Series-connected batteries used to produce a higher voltage. The same current passes through all the cells, but each cell voltage can vary. Charge balancing becomes a significant issue for a long string of 50 or more cells.

C-rate The rate at which a battery can deliver or accept current, stated in terms of the rated capacity of the cell in amp-hours. This may also be referred to as the hour rate, such as the 1-h rate.

Cell An individual electrochemical device that converts between chemical energy and electrical energy. The cell construction, open circuit voltage, energy, and power density, all depend on the chemistry of the cell (see section "Battery Chemistries").

Coulombic efficiency Ratio of charge delivered by a rechargeable battery during discharge cycle to the charge stored during charge cycle.

Depth of discharge (DoD) An alternate method to indicate the state of charge of the battery; it is the reciprocal of SoC.

Direct current (DC) Unidirectional current that continually flows only in one direction. Sources such as batteries, fuel cells, and solar cells produce electricity in the form of direct current.

Memory effect An effect observed particularly in nickel cadmium batteries in which the cells gradually lose capacity when subject to repeated partial discharges followed by complete recharges cycles. This electrochemical effect is different than the loss of capacity due to aging and use. In some cases, a series of full discharge/recharge cycles can restore some or all of the lost capacity due to the memory effect but not due to cycle life or aging.

Proportional-integral (PI) controller A type of linear feedback control in which an error signal is calculated as the difference between a measured signal and the desired reference set point. The controller attempts to adjust the operation of the process using a weighted combination of the present error

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(proportional term) and accumulated past error (integral term).

Primary battery One-time-use batteries not capable of being recharged. They are discarded or preferably recycled once the stored energy has been depleted. These types of batteries will not be considered in this article.

Root mean square (RMS) A scalar quantity that is computed from the square root of the sum of the squares of a dataset and is commonly used to represent a voltage or current over one cyclical period. Average power is the product of the RMS current and RMS voltage.

Secondary battery Commonly referred to as rechargeable batteries, they can be repeatedly recharged electrically by passing current through them in the opposite direction to that of the discharge current. Secondary batteries are of significant interest for their ability to store and supply energy and are the focus of this article.

Self-discharge rate The rate at which a battery discharges, or looses stored energy, due to internal cell reactions.

SLI batteries Starting, lighting, and ignition (SLI) batteries are used in automobiles. These batteries are usually characterized by a high discharge rate.

State of charge (SoC) Defined as the capacity left in a battery expressed as a percentage of some reference. SoC of a battery is usually expressed as a percentage of the current battery capacity when it is fully charged.

State of health (SoH) A metric that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It takes into account factors such as charge acceptance, internal resistance, voltage, and self-discharge. It is an estimate rather than a measurement.

Watt-hour (Wh) A unit of energy, the amount of power delivered for 1 h. It is equivalent to 3,600 Joules of energy.

Definition of the Subject

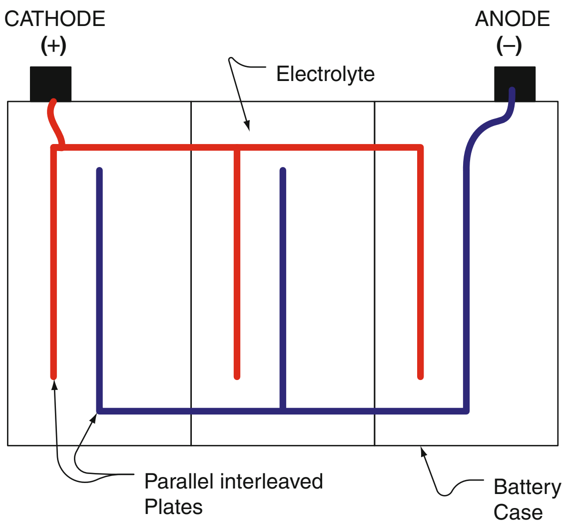
Batteries, both primary and rechargeable, are important energy storage devices ubiquitous in our daily, modern lives. Whether in our handheld portable electronics, conventional or hybrid/electric cars, or in the electrical "grid," battery technology will continue to evolve as technology improvements increase storage capacity and lifetime and reduce cost.

Introduction

Batteries are perhaps most synonymous with portable power such as flashlights and personal electronics like cell phones, music players, and laptops to name a few modern examples. We have become trained to monitor the battery "bars" to determine how much more we can talk, e-mail, or surf the "net." Batteries are far more prevalent, however, and they tend to be underappreciated, such as the ones in our automobiles which perform dutifully until suddenly, usually after years of neglect, they fail to start our car. An electrical power system is the ultimate in just-in-time manufacturing in that electricity generation and consumption must be perfectly balanced at all times. This imposes difficult operating constraints on the system when variability on both the load side and source side exists, such as with renewable energy sources like wind and solar. Therefore, energy storage is important to ensure that electricity can be generated and energy stored generated when the source is available, and the load can continue to be supplied when the variable, renewable energy source is insufficient. While there are many technologies for energy storage, batteries play an important role to improve the electric power system asset utilization, energy availability, reliability, and performance. Several large-scale, high-energy battery technologies hold promise of providing economical energy storage for a wide range of these power system and energy management applications.

This chapter will discuss issues related to batteries, battery charging, and battery management. The first section will provide an overview of the different types of battery chemistries. The focus in this chapter is on rechargeable batteries which can accept, store, and then deliver energy at a future point in time. Subsequent sections will discuss circuits to charge and manage the batteries.

A detailed description of internal construction of the individual cell is beyond the scope of this chapter, but it is sufficient to consider that a battery is typically comprised of electrodes, electrolyte, and some form of case



Batteries, Battery Management, and Battery Charging Technology. Figure 1
Conceptual illustration of a lead-acid battery with parallel, interleaved plate that comprises the anode and cathode. The electrolyte can be a liquid or a gel, and the enclosure can be vented or sealed

or enclosure as shown in Fig. 1. Various materials are commonly used, each with advantages and disadvantages. The voltage, current rating, and storage capacity are all functions of the material and construction.

Battery Failure

Some of the most common causes for battery failure are short circuiting of battery terminals, improper charge control while charging secondary batteries, improper polarity connections while charging a battery, and a long period of use. Internal failure modes include thermal runaway which is a major problem in lead-acid batteries, loss of electrolyte by gassing, mechanical damage, and warping of plates due to an excessively high rate of discharge.

Methods of Charging

Float charge is most commonly used for non-sealed lead-acid batteries, which can tolerate sitting at an elevated voltage for prolonged periods of time. The original meaning of the term stems from the telecom industry's jar batteries in which the liquid electrolyte was exposed to the atmosphere and the batteries "sat on float" at a continuous elevated voltage to be sure they were fully charged when called upon to back up the telephone equipment. In this mode of operation, the charging current depends on the state of charge of the cells, and the current gradually declines to a minimum value as the cells become fully charged. Float charging could result in continuous out gassing which reduces the level of water in the electrolyte. Hence, float charging of lead-acid batteries often requires "watering" of the batteries to maintain the level of electrolyte.

Trickle charge is used to maintain a battery at a full state of charge by supplying a small current to offset the self-discharge characteristics of the battery. Some battery chemistries, like the lead-acid varieties, have relatively high self-discharge rates and can lose their ability to hold a charge when stored discharged for a long period of time due to sulfation, the crystallizing of the lead sulfate. A trickle charger, sometimes called a "battery tender" is often used in automobile, boats, motorcycles, RV and other seasonal equipment where the battery can sit for months without use.

Bulk charge involves restoring the majority of the energy storage capability of a battery. Hence, a bulk charge may be followed by an equalizing charge.

Equalization charge is the final stage of charging for a series-connected battery string in which the SoC of individual cells are forced to the same value. For lead-acid batteries, this can be as using a higher charging voltage. The cells with higher SoC begin to outgas while the weaker cells "catch up." Other battery chemistries cannot tolerate overvoltage charging. Charge balancing techniques will be described in detail in the next section.

Rapid charge involves quickly recharging a battery at a high C-rate. Depending on the battery chemistry, this mode of charging may only replace a portion of the full capacity. It is usually imperative to monitor the cell temperature rise during rapid charging to avoid excessive outgassing or thermal runaway.

Regardless of the mode of charging, the charging types include constant-current charging and constant-current–constant-voltage charging (constant-current charge until current attains a flat profile, then constant-voltage charging takes over).

Battery Chemistries

A wide variety of battery electrochemistries are available today. While there is a clear evolution of technological progress, each technology has advantages and disadvantages that make them more or less suited for different applications. This section presents an overview of commonly available technologies and explores their general characteristics, advantages and disadvantages, and charging considerations.

Lead Acid

General Characteristics

Lead-acid batteries are by far the most common battery type and represent approximately 40–45% of the total global battery sales. Lead-acid batteries are available in large quantities and in a variety of sizes and designs. They are manufactured in sizes from smaller than 1 Ah to several thousand Ah. Design variations to electrode plates enable them to perform as batteries with high discharge rate and low-energy (automobile starting applications) and also for deep-cycle applications with moderate discharge rates.

The world's largest battery-based energy storage system is a 40-MWh battery located in Chino, California. It uses individual industrial-size lead-acid cells in series and parallel connection to make a 10-MW system capable of delivering energy into the utility grid at 2,000V and 8,000A for 4h.

Advantages and Disadvantages

Advantages include:

- One of the main reasons for the popularity of lead-acid batteries is that they can be manufactured on a local basis worldwide with high rates of production.
- Traditionally, they have been used as starting-lighting-ignition (SLI) batteries in automobiles, though now they are being slowly phased out by high-performing nickel cadmium and nickel metal hydride batteries.
- They have a high cell open-circuit voltage of 2.0 V which is one of the highest for aqueous electrolyte systems.
- SoC estimation is very easy in the case of lead-acid batteries. The specific density of electrolyte bears a direct relation to the SoC of the battery.
- It provides good charge retention for intermittent charge applications.
- Cell components can be easily recycled.
- They are very cheap compared to other secondary battery designs.
- They are also available in maintenance-free designs.

Disadvantages include:

- Lead-acid batteries require frequent maintenance. These batteries lose water while in operation, and the water level needs to be replenished.
- As they employ lead in their construction, they are usually heavy and not conducive for portability.
- Lead-acid batteries have a relatively low cycle life (50–500 cycles). However, up to 2,000 cycles have been achieved with cell design improvements, heavily derating the discharge capacity and using active charge equalization techniques (see section "Cell Charge Equalization").
- One of the major drawbacks is the thermal runaway problem. It can occur due to improper design of battery or charger.

Application Examples Lead-acid batteries are commonly installed in uninterruptible power supply (UPS) systems, in renewable and distributed power systems. Traditionally, they were used as SLI batteries in automobiles. Other applications include telephone systems, power tools, communication devices, emergency lighting systems, and as the power source for mining and material-handling equipment.

Charging Characteristics Lead-acid batteries do not exhibit memory effect. However, it is very vital to have the correct charge and float voltages to achieve a long life. Charging up to the rated voltage level is a must; any deviation from this voltage level leads to electrode corrosion or negative plate sulfation in the long run. Lead-acid batteries used for deep-cycle applications usually have a short life of about 300 discharge/charge cycles.

Lead-acid batteries are typically charged in three stages, which are constant-current bulk charge, equalization final charge, and float charge. The *constant-current charge* provides bulk of the charge and takes up about half of the required charge time. The *equalizing charge* continues charging at a lower charge current and ensures all cells are fully charged and the

state-of-charges are similar. This may be done through active techniques or simply overcharging some cells to ensure the undercharged ones receive a full charge. The *float charge* compensates for the self-discharge loss when a battery sits unused for a period of time.

Valve-Regulated Lead Acid (VRLA)

General Characteristics The valve-regulated lead-acid (VRLA) battery is a completely sealed cell, which prevents electrolyte loss due to outgassing, and hence alleviates the need to water the cells. The VRLA battery incorporates the gas recombination principle which allows the oxygen generated at normal overcharge rates to be reduced at the negative plate, eliminating oxygen outgassing. If the rate of outgassing exceeds the rate of recombination, the partial pressure of hydrogen builds up and can cause the vent to open, which destroys the cell.

Advantages and Disadvantages

Advantages include:

- VRLA batteries do not require "watering" as is the case with other types of lead-acid batteries since the water level is maintained due to a regenerative cell reaction. Thus, VRLA batteries do not require the frequent maintenance for battery operation, which is an advantage over the conventional lead-acid battery.
- Battery cells can be packaged more tightly because of sealed construction and immobilized electrolyte, hence the footprint and weight of the battery are reduced.
- SoC is measured by measuring the voltage (The open-circuit voltage can therefore be used to approximate the state of charge). The measurement of the open-circuit voltage to determine the SoC is based on the relationship between the electromotive force and the concentration of the sulfuric acid in the battery.
- One of the major advantages with VRLA batteries is that they do not experience memory effect which is common with nickel cadmium batteries.

Disadvantages include:

- These batteries have a shorter life span than other types of lead-acid batteries. In UPS applications, a life span of 5–10 years is typical since their life reduces due to harsh operating conditions.
- They should not be stored in discharged condition.
- These batteries are sensitive to higher temperature environment. As with most batteries, the capacity is dependent on the discharge rate and temperature; the capacity decreasing with decreasing temperature and increasing discharge rate.
- Electrolytes act as heat sinks in batteries. However, VRLA batteries are "acid starved" as they use much less electrolyte, hence they do not have an effective heat-sink mechanism which makes them more prone to thermal runaway condition than compared to flooded lead-acid batteries.
- They have low cell resistance; hence immense short-circuit current is available.

Application Examples Because the VRLA batteries are sealed, they are ideal for many consumer applications. They are found in many uninterruptable power supply systems for computers, and as backup power for other electronics' light security systems, and emergency lighting. Because high discharge rates are possible, they are also advantageous for engine starting.

Charging Characteristics Constant-voltage charging is the most efficient and fastest method of charging the VRLA battery. To carry out fast charging of VRLA battery, the charger must be capable of charging the battery at the $2C$-rate. Fast charging is usually possible with a full charge achieved within 4 hours, and some batteries that accommodate even higher C-rates can charge so that they are returned to full capacity within 1 h. When float charging is used, the charger maintains each cell at 2.3–2.4V in order to ensure a complete charge and maximum battery life.

Nickel Cadmium (Ni-Cd)

General Characteristics Nickel-cadmium battery is a very reliable, sturdy, long-life battery. Little maintenance is needed on nickel-cadmium batteries. These batteries have two major variants based on the intended application. Cells with thin sintered plates have low internal resistance and have a high power to volume ratio, while cells with thick electrode plates have a high energy storage capacity. Nickel-cadmium batteries are manufactured as unsealed open/semi-open batteries

in which electrolyte/gas can escape through a vent (vented Ni-Cd batteries) and as fully sealed batteries which do not require topping up of the electrolyte with water. Nickel-cadmium batteries exhibit voltage suppression, also called as memory effect. The memory effect causes the battery to deliver only the capacity, which was used during the repeated charge/discharge cycles before. Because of this, the whole capacity of Ni-Cd batteries should be used for each discharge cycle to avoid a decrease of the maximum capacity. "Memory effect" makes this battery less suited for applications that don't allow a complete discharge.

Advantages and Disadvantages

Advantages include:

- They have a longer life than compared to lead-acid batteries.
- Extended operating temperature range compared to lead-acid batteries. This makes them more flexible in heavy duty applications in regard to temperature range.
- Extremely rugged batteries.
- Good charge retention. They can be stored for long periods without significant deterioration of SoC.
- These batteries require less maintenance.

Disadvantages include:

- Cadmium is an environmentally hazardous substance. Hence, disposal of Ni-Cd batteries is a major issue.
- They exhibit strong voltage depression (memory effect) phenomenon. This is a major drawback of Ni-Cd cells.

Application Examples Because of their favorable electrical properties, excellent reliability, low maintenance, rugged design, and long life, nickel-cadmium batteries are used in a large variety of applications. Unsealed Ni-Cd with higher capacity ranges are used in high-energy applications such as traction and large emergency power installations. Industrial nickel-cadmium batteries are used in train lighting and air conditioning for rail cars, emergency and standby systems such as emergency brakes and lighting in mass-transit and subway cars, diesel-engine cranking in locomotives and commuter cars, railroad signaling, communication along tracks, as well as standby power in rail stations and traffic control systems. The nickel-cadmium battery is also used in power-generating stations and power distribution. Sealed Ni-Cd batteries are usually of a low energy storage type (30 Ah). These are extensively used in consumer electronics, domestic markets, and low-energy applications.

Charging Characteristics Constant-voltage charging is the preferred method for unsealed nickel-cadmium batteries.

Nickel-Metal Hydride (Ni-MH)

General Characteristics Nickel-metal hydride (Ni-MH) cells share many of the same characteristics as nickel-cadmium cells and reduce some of the disadvantages. A major difference between nickel-metal hydride and nickel-cadmium cells is that cell reaction of nickel-metal hydride cells is exothermic, and hence, internal temperature of Ni-MH cell rises when it is in operation. On the other hand, nickel-cadmium cells have an endothermic cell reaction.

Advantages and Disadvantages

Advantages include:

- These batteries do not pose environmental hazards like Ni-Cd batteries.
- They possess higher specific energy and energy density than nickel-cadmium cells.
- Bipolar battery pack designs are popular as the energy storage in hybrid vehicles.

Disadvantages include:

- Overcharging leads to serious consequences for the battery; it leads to battery heating which in turn releases hydrogen gas and increases fire hazard. As a result, Ni-MH batteries require complex charging circuitry to ensure overcharging does not take place.
- Complex circuitry for charging implies Ni-MH cells cannot be charged on conventional battery chargers. This necessity contributes to an increased cost for Ni-MH battery.
- Limited service life of about 200–300 cycles if repeatedly discharged at high load currents.

- Higher self-discharge rate than Ni-Cd. Hence, the shelf-life of a fully-charged Ni-MH battery is much shorter. The shelf life is improved by adding chemical additives, which lowers the energy density.
- Memory effect is present but to a much lesser extent than Ni-Cd battery.

Application Examples The nickel-metal hydride battery used to be incorporated in computers, cellular phones, and other consumer electronic applications. In recent years, lithium-ion battery has replaced nickel-metal hydride batteries as it possesses a superior specific energy and energy density.

Charging Characteristics Repeated high load current discharging reduces the service life of nickel-metal hydride batteries to about 200–300 cycles. Ideal discharging of these batteries usually occurs at load currents of 0.2–0.5*C*. Ni-MH battery suffers from a high self-discharge rate. Self-discharge rates are reduced by adding chemical additives to the cell. However, this results in a trade-off, as chemical additives that slow down the self-discharge rate decrease the energy density of the cell. For a particular make of battery, it has been observed that it loses about 32% of charge if stored for about 80 h.

Lithium Ion (Li-Ion)

General Characteristics Lithium-ion cells are often specified for use in high-performance applications where small size and high performance are of paramount importance. They have higher specific energy and energy density than nickel-metal hydride cells. High energy density of Li-ion cell also makes it less stable. These cells pose a potential fire hazard if not managed properly.

Advantages and Disadvantages

Advantages include:

- Li-ion cells have a long cycle life (3,000 cycles at 80% depth of discharge). Hence, they are suited for applications which require a large number of charge-discharge cycles.
- They can operate over a wide temperature range.
- Low self-discharge rate leads to a long shelf life for these batteries.
- Rapid charge capability endears these batteries with consumer electronics applications.
- High energy efficiency. These cells can be up to 94% efficient in terms of energy over a cycle.
- No "memory effect."
- These batteries do not pose an environmental hazard as they are not made up of toxic materials.
- High energy density (300–400 kWh/m^3, 130 kWh/ton).
- One of the salient qualities of Li-ion cells is that they have a very high coulombic efficiency as compared to lead-acid cells. A new Li-ion cell exhibits up to 94% coulombic efficiency as against a lead-acid battery which has only 80% coulombic efficiency.

Disadvantages include:

- Li-ion cells have a moderately high initial cost.
- High energy density of Li-ion cells also gives rise to instability and fire hazard issues. This behavior of Li-ion cells makes it mandatory to have a complex protective circuitry. The battery management systems for Li-ion cell must be able to prevent overcharging of these cells. Overcharging in Li-ion cells leads to thermal runaway and subsequently a fire hazard.
- Venting and thermal runaway may take place when cells are crushed.
- Li-ion batteries composed of series strings of cells require charge equalization modules. Li-ion cells do not support low cost, easy to implement passive cell-balancing schemes.

Application Examples Li-ion batteries are employed in high-performance applications where size and energy are important. They are the preferred choice for consumer electronics such as laptop computers, cellular telephones, and personal media player where long battery life is required. The suitability for use in military, aerospace, and automobile applications is also being explored.

Charging Characteristics Li-ion cells are fabricated in discharged state and thus must be charged before

use. The cells are typically charged using either a constant current (CC) or a constant current-constant voltage (CCCV) with a taper charge regime. Exceeding the maximum voltage is a potential safety hazard and can result in irreversible damage to the battery. At the same time, charging to a lower voltage reduces the capacity of the battery. The construction of these batteries tends to make them susceptible to internal short circuits due to impurities. With the demand for higher energy density, an internal short can lead to catastrophic consequences including the risk of fire. Hence, internal temperature rise of the battery pack needs to be monitored as well as cell voltage. These considerations make it crucial to incorporate special control circuitry for lithium-ion batteries for management of charge and discharge. Although Li-ion cells have a flat voltage profile, it has been established in literature that cell open-circuit voltage provides a good estimate of the state of charge (SoC) ranging from 20% to 100%.

Sodium Sulfur (Na-S)

General Characteristics A sodium-sulfur battery is a type of molten metal battery constructed from sodium (Na) and sulfur (S). This battery has a high energy density, high efficiency of charge/discharge (89–92%), and long cycle life, and is fabricated from inexpensive materials. Sodium sulfur batteries usually have operating temperatures of 300–350°C. They are most prominently found in power grid operations, electric trains, and wind generation operations.

Advantages and Disadvantages

Advantages include:

- These batteries are constructed from inexpensive materials.
- Per unit volume, sodium sulfur batteries deliver three to five times more energy than lead-acid batteries. They have a high specific energy in the range of 160 kW/h.
- Designed to last 15 years through 2,500 full charge/discharge cycles.
- It has up to 89% cell DC efficiency with no self-discharge.
- Insensitive to ambient temperatures which make it suitable to be housed outdoors.
- Extremely fast charge cycling; it can transit from full charge to full discharge in milliseconds.
- Sodium sulfur battery facilitates remote operation and monitoring along with the added benefit of minimum maintenance.

Disadvantages include:

- These batteries require an elaborate thermal management system to ensure energy efficiency.
- Cells need to be hermetically sealed when operated in corrosive outdoor environments.

Application Examples Sodium-sulfur batteries have operating temperatures of 300–350°C and extensively employ sodium polysulfides which are highly corrosive. These considerations make Na-S batteries suitable for large-scale nonmobile applications such as grid energy storage. Sodium-sulfur batteries have many applications in power systems. They are used to provide additional power during voltage sags. They provide prompt spinning reserves for grid frequency control and reactive power support. Sodium-sulfur batteries also perform admirably in stabilization of wind energy fluctuations by providing the necessary additional power. Na-S batteries are a possible energy storage technology to support renewable energy generation, specifically wind farms and solar generation plants. They are also a better option as against pumped hydroelectric storage schemes. In Europe, motivation is toward implementing Na-S batteries for automotive traction applications.

Lithium-Iron Monosulfide

General Characteristics Practical energy densities of 100 Wh/kg are achieved by secondary lithium-iron monosulfide cells. Lithium-iron sulfide batteries require a thermal management system to maintain optimum operating temperatures. Precise voltage monitoring is needed from the charger. This battery system requires a thermal management system to maintain the rated operating temperature for the battery and a specialized charger in which careful voltage control is maintained. This battery technology was under active research in the 1970s for electric vehicles. It is yet to be commercialized.

Nickel Zinc (Alkaline Rechargeable System)

General Characteristics The nickel-zinc (zinc/nickel-oxide) battery is an alkaline rechargeable system. Currently the nickel-zinc system is capable of delivering about 50–60 Wh/kg and 80–120 Wh/L depending on the specific design. Nickel-zinc batteries are suited for high discharge rate applications such as a camera flash.

Advantages and Disadvantages

Advantages include:

- Good capacity retention has made it a competitor of silver-zinc and silver-cadmium systems. Fully charged nickel-zinc batteries lose about 20% of their original capacity within a month when left on open-circuit at 25°C. Nickel-zinc batteries can be stored for up to 3 years.
- It has a wide range of temperature tolerance (−39°C to +81°C operating temperature).
- One of the major plus points is that it has a flat discharge voltage profile for a significant portion of the discharge.
- Ni-Zn battery possesses a fast recharge capability.
- It has a sealed maintenance-free design.

Disadvantages include:

- The main stumbling block for the success of Ni-Zn battery technology is that Ni-Zn battery possesses a poor cycle life (up to 150 cycles).
- It has a relatively low volumetric energy density.

Application Examples Nickel-zinc provides a very low-cost option for a long-cycle-life alkaline-rechargeable system. The nickel-zinc system is suited for mobile applications such as electric bicycles, electric scooters, electric and hybrid vehicles, or other deep-cycle applications. Deep-cycle applications for nickel-zinc batteries include trolling motors, electric bicycles and scooters, wheelchairs, golf carts, electric lawnmowers, electric vehicles, and similar uses. Nickel-zinc batteries have the required discharge-rate capability, high cycle life at deep depths-of-discharge, lightweight rugged construction, and are capable of being stored over the winter months without any maintenance charging.

Charging Characteristics The battery should be protected from excessive overcharge and over discharge. Extreme abuse may reduce battery performance and cycle life or cause a potential safety hazard.

Metal Air

General Characteristics The most popular metal-air battery is the zinc-air electrode battery. Zinc-air secondary batteries are being developed which can store three times as much as lithium-ion batteries but only cost half as much. The intended applications include cell phones, portable consumer electronic items, and electric vehicles. Lithium-air, calcium-air, and magnesium-air batteries have also been studied, but cost and problems such as anode polarization or instability, parasitic corrosion, nonuniform dissolution, safety, and practical handling have so far inhibited the development of commercial products.

Advantages and Disadvantages

Advantages include:

- Zinc-air battery has high energy density. Suitable for electric vehicle technologies.
- Zinc-air cells intake air with CO_2 removed. Earlier, this was seen as a disadvantage. However, deployment of this cell on electric vehicles with a CO_2 filter will lead to drastic reduction in CO_2 emissions. Hence, this cell is being proposed as a likely candidate for automotive applications.
- Zinc-air cells have a flat discharge voltage profile.
- These cells have a long shelf life (dry storage).
- Zinc-air battery has a safe battery chemistry which reduces fire hazards greatly.

Disadvantages include:

- Main difficulty in the development of rechargeable zinc-air battery is the deactivation in performance of air electrode after a few charge/discharge cycles.
- Internal short circuit is a major problem in Zn-Air secondary cells. Internal short circuit usually occurs after several charge/discharge cycles due to zinc dendrite growth through the separator.
- Depending on the discharge rate, the energy capacity of the cell drops drastically.

- Drying out of electrolyte limits shelf life once opened to air.
- Limited operating temperature range.

Application Examples Future applications for rechargeable zinc-air batteries include cell phones and electric vehicles. The high energy density, low-cost constituent materials, and relatively safe cell chemistry are some of the positive application advantages of this battery type. However, more efforts are required to increase the number of charge/discharge cycles of this battery before it becomes practical for commercial use.

Zinc-Bromine

General Characteristics The zinc-bromine battery is a high-energy-density battery. There are no toxic materials in this battery system. Zinc-bromine battery is constructed from low-cost materials; the battery cells are made up of plastic. It provides a viable energy storage option for a variety of generation sources and is ideally suited for applications requiring 2–10 h of energy storage. The energy density of this advanced battery makes it attractive for applications where traditional energy storage batteries, such as lead-acid batteries, are unacceptable due to size and weight restrictions. The zinc-bromine battery is a flow battery. Auxiliary systems are required for circulation and temperature control of the electrolyte. The zinc-bromine battery has a good shelf life. These batteries are more prominent in the high energy range: 10–500 kWh. These battery systems are custom built for specific applications.

Sodium-Beta

General Characteristics Sodium-beta batteries are high-temperature operating systems and hence have high energy density compared to ambient temperature systems.

Advantages and Disadvantages

Advantages include:

- Sodium-beta batteries are characterized by high energy density, lack of required maintenance, and performance independent of ambient temperature.
- They have a potential for low cost (relative to other advanced batteries) and are cheap as raw materials.

Disadvantages include:

- Thermal management is critical. Requires thermally insulated battery enclosure.
- These batteries operate in the region of 160–500°C. Hence, these batteries must not be affected by ambient temperatures.

Application Examples Sodium-beta battery technologies have been developed for use in relatively large-scale energy storage applications (10–1,000 kWh). Sodium-beta batteries can be used at generation facilities for load leveling, spinning reserve, and area regulation. They are also used for line stability and voltage-regulation purposes at distribution facilities. This technology is also suitable for peak demand reduction and power quality maintenance at a customer site. Sodium-beta batteries have also been investigated for their suitability in traction applications since, for a given physical envelope, sodium-beta batteries can provide significantly greater energy (range) at a reduced weight while meeting the vehicle power requirements compared with conventional battery technologies.

Battery Charging Circuits

Battery Charging Techniques

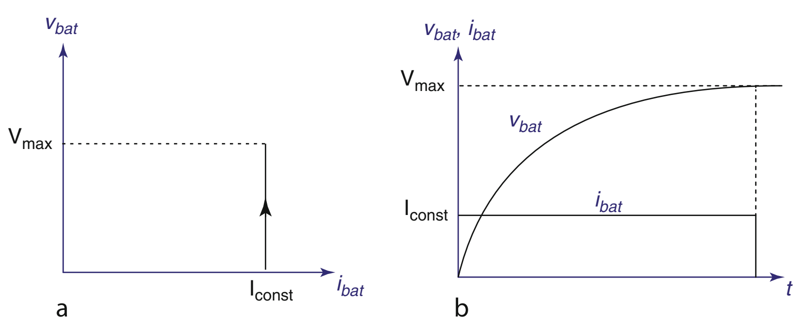
Proper battery charging techniques can significantly improve battery performance and life cycles. Thus, several factors such as fast charging, good quality of charging current, and avoiding under and over charging are considered. In particular, over charging can damage battery's physical components while under charging can reduce its energy capacity. Therefore, an appropriate control technique for charging process should be adopted. Different battery charging techniques are presented in this section. Operating principle of the battery charge controller is discussed for each technique, and the block diagram of the controller is depicted. Depending on the selected charging technique, output voltage or current of the converter are fed back to the charge controller circuit. Each charging technique has a charging characteristic curve which is defined as the voltage-current trajectory of the battery during the charging period (v_{bat} versus i_{bat}).

Constant-Current Charging (CC) Constant-current charging is the most conventional battery charging technique. In the charging characteristic curve shown in Fig. 2a, the battery current is kept constant while battery voltage increases during charging until it reaches the maximum allowed value (i.e., rated voltage of the battery). Figure 2b shows the voltage and current profiles of the battery during the charging period. When the battery voltage has reached its final value, the charge controller circuit disconnects the battery from the converter to avoid overcharging and consequent battery failure. The voltage profile of the battery during the charging and discharging intervals is not necessarily linear, as shown in Fig. 2b, and depends on the type of the battery.

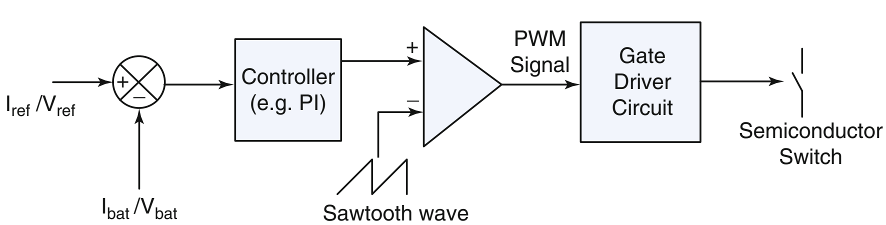
Figure 3 shows the associated control block diagram. The output current is compared with the reference current to produce the error current. The error current is fed to a proportional-integral (PI) controller to eliminate steady state error and generate the command signals for switching of the charger power electronic circuits.

The main advantage of this method is its simplicity. The converter circuit can be realized by an AC-DC or DC-DC converter based on the input type. Moreover, the output capacitor can be dropped as the output voltage regulation is not required, and regulating merely the output current is sufficient. Elimination of the output capacitor simplifies the converter circuit to a first-order current filter which can be analyzed simply and implemented inexpensively. Fast charging can be realized by large current pumping; however, this has the potential to degrade the internal chemical reactions in the battery. Alternatively, the low charging current prolongs the charging time. Therefore, proper choice of the charging current is crucial for enhancing the charging performance and increasing the lifetime of the battery charging system.

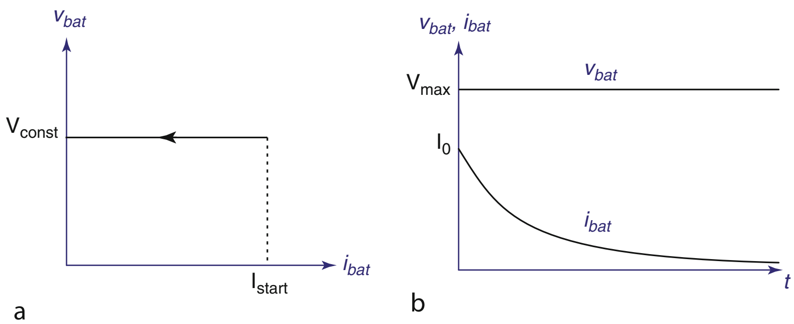
Constant-Voltage Charging (CV) Constant-voltage charging is another conventional battery charging technique. The charging characteristic curve of this technique is illustrated in Fig. 4a. In this method, the



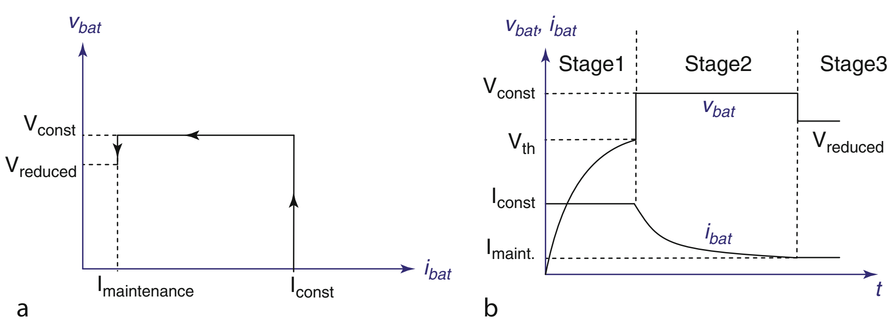
Batteries, Battery Management, and Battery Charging Technology. Figure 2
(**a**) Charging characteristic curve of the constant-current technique; (**b**) Current and voltage profiles of the battery during the charging process



Batteries, Battery Management, and Battery Charging Technology. Figure 3
Block diagram of the controller circuit useful for constant-current or voltage charging



Batteries, Battery Management, and Battery Charging Technology. Figure 4
(**a**) Charging characteristic curve of the constant-voltage technique; (**b**) Current and voltage profiles of the battery during the charging process



Batteries, Battery Management, and Battery Charging Technology. Figure 5
(**a**) Charging characteristic curve of the CC-CV technique; (**b**) Current and voltage profiles of the battery during the charging

battery voltage remains constant while the battery current is decreasing and eventually becomes very low. The current and voltage profile during charging is shown in Fig. 4b. This initial high current (I_o) temporarily increases the battery temperature and can degrade the battery, depending on the chemistry. The battery charge controller disconnects the battery from the charger circuit when the current reaches a specific amount (I_{min}), as shown in Fig. 4b. The control block diagram is shown in Fig. 3, where the sensed and reference variable is the battery and reference voltage, respectively.

Similar to the CC methodology, the CV charging strategy is straightforward and easy to implement. As opposed to the CC charging strategy, a capacitive output is required to regulate the output voltage. This output stage increases the model order, and therefore, the controller design process is slightly more complex than CC technique, yet simple enough for low-cost applications.

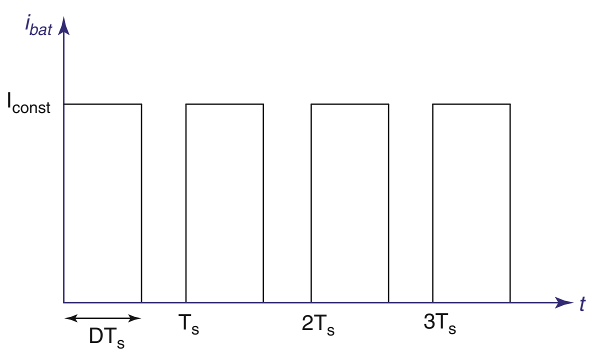
The main disadvantage of the CV charging methodology is the temperature rise of the battery during initial charging stages. While the internal voltage of the battery is very low, the applied voltage at the terminal of the battery is relatively high. Thus, considering the small internal resistance of the battery, a large current will flow which can damage the battery. Another drawback of CV charging is the long charge time due to very low currents at the final stages of the charging.

Mixed Constant-Current and Constant-Voltage Charging (CC-CV) The CC-CV charging technique utilizes both CC and CV charging. Figure 5a, b illustrates the charging characteristic curve and

current-voltage profiles of this method, respectively. The charging is performed in three stages. First, the battery current is kept constant until the battery voltage reaches a predetermined value (V_{const}). Then, the battery voltage is kept constant while the battery current drops below a specific value (I_{min}). The final stage is the float charge stage where the battery voltage is reduced to compensate for the loss caused by self-discharge of the battery.

Since the current is kept constant at the first charging stage, the current rush disadvantage of CV charging technique is avoided. Also, since the voltage is kept constant at the second stage, the overcharging disadvantage of CC charging is avoided. Moreover, the float charging stage keeps the battery in full charge for a long time without degrading the battery. These advantages of CC-CV charging technique make it perfect for applications with high performance requirement. However, the design complexity makes this option more expensive compared to either CC or CV techniques.

Pulse Charging Pulse-charging technique is inherently a CC charging method that uses a pulsating charging current. This pulsating current causes the ions to distribute evenly throughout the battery and electrodes. Consequently, even distribution of ions prolongs the lifetime of the battery and enhances the charging performance. Figure 6 shows the current profile of the battery using pulse-charging technique. Due to the internal battery resistance, the battery voltage



Batteries, Battery Management, and Battery Charging Technology. Figure 6
Current profile of the battery using pulse-charging technique

increases slightly during the charging subintervals. DC value of the charging current can be controlled by the duty cycle of applied current between zero and I_{max}. The charging rate is controlled by the DC value of charging current; thus, charging time of the battery can be controlled by the duty cycle:

$$t_{charge} = f(I_{DC}) = f(DI_{max}), \tag{1}$$

where D, I_{DC}, and I_{max} are the duty cycle, DC value, and the maximum of the battery current, respectively. Large duty cycles are applied during the initial stages of charging to ensure fast charging. After battery voltage is increased sufficiently, the duty cycle gradually decreases to prevent overcharging and consequent battery failure.

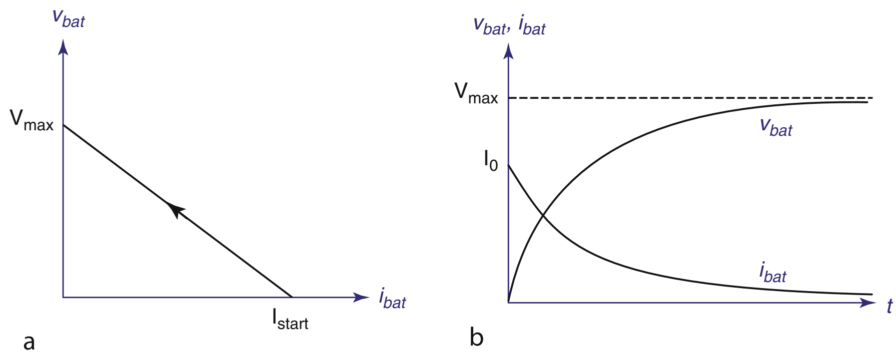
Pulse current charging needs an extra control loop to regulate the duty cycle of the reference current (I_{ref}) by the output voltage. As the output voltage decrease, this additional control loop decreases the duty cycle and consequently the DC value of the charging current. Following a pulsating reference current requires a fast control loop. The bandwidth of the control loop should be sufficiently higher than the switching frequency. This bandwidth is limited by the effective bandwidth of the current sensor. Thus, increasing the bandwidth of the controller requires high-bandwidth current sensors, which can be costly.

Taper Characteristic Charging In taper charging, neither battery current nor battery voltage is kept constant. Instead, a linear combination of battery voltage and current is kept constant:

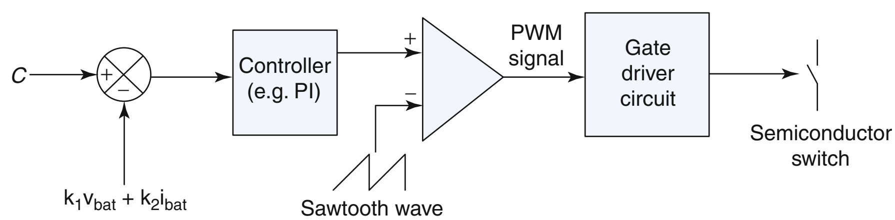
$$k_1 V_{bat} + k_2 I_{bat} = c = \text{constant}, \tag{2}$$

where k_1 and k_2 are constant coefficients which are determined by design requirements. CC and CV charging techniques are special cases of the taper characteristic charging in which $k_1 = 0$ or $k_2 = 0$, respectively. Figure 7a, b illustrates the charging characteristic curve and voltage-current profiles of the taper charging technique, respectively.

The block diagram of the charge controller using this technique is depicted in Fig. 8. Sensing of both battery voltage and current is required and is the main drawback of this strategy. Sensors are usually the most expensive components of the converter circuits, and increasing the number sensor may drastically increase the total cost of the system.



Batteries, Battery Management, and Battery Charging Technology. Figure 7
(**a**) Charging characteristic curve of the taper-characteristic-charging technique; (**b**) Current and voltage profiles of the battery during the charging



Batteries, Battery Management, and Battery Charging Technology. Figure 8
Block diagram of the controller for taper characteristic charging

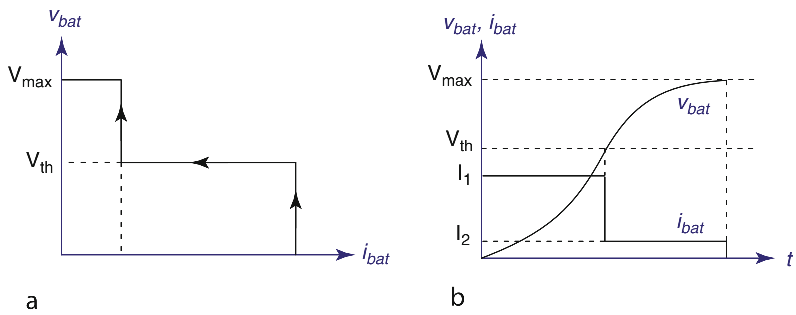
Assembled Characteristic Charging Assembled or modified charging is a technique whose characteristic curve is a combination of CC, CV, or taper characteristic curves. In this technique, when a certain threshold is reached (e.g., certain voltage), the characteristic curve is changed from one technique to another. Two conventionally assembled characteristic charging methods are assembled constant-current charging and assembled taper characteristic charging.

Assembled Constant-Current Charging Figure 9a illustrates the charging characteristic curve of the assembled constant-current charging technique. As seen in Fig. 9a, battery is charged by a high constant current (I_1) until the output voltage reaches the threshold voltage (V_{th}), after which the CC charging will continue using a lower constant current (I_2). Then, charging with low current will continue until the output voltage reaches its maximum value (V_{max}), which is usually the rated voltage of the battery. The current and voltage profiles of the battery are shown in Fig. 9b.

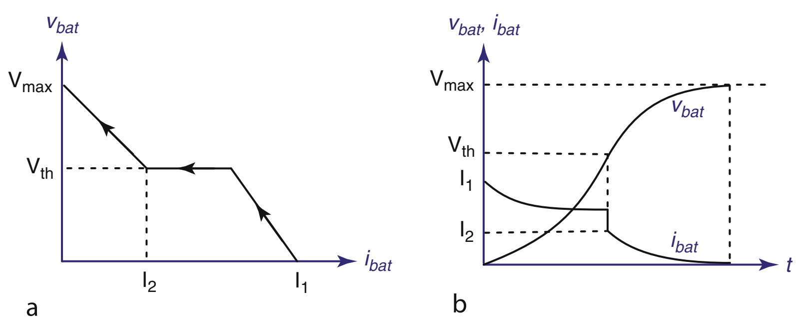
As the high constant current reduces the charging time but increases the risk of overcharging, one may trade off between fast charging and overcharging protection. This drawback of CC charging has been overcome in assembled constant-current technique. Short charging time can be achieved by using high constant current (I_1) at the first stage ($v \leq V_{th}$), while overcharging can be avoided by using low constant current at the second stage ($v > V_{th}$).

Assembled Taper Characteristic Charging Assembled taper characteristic charging utilizes two different taper charging characteristic curves, as shown in Fig. 10a. The characteristic equation of this technique can be expressed as:

$$\begin{cases} k_1 V_{bat} + k_2 I_{bat} = c, & V_{bat} \leq V_{th} \\ k_1' V_{bat} + k_2' I_{bat} = c', & V_{bat} \geq V_{th} \end{cases} \tag{3}$$



Batteries, Battery Management, and Battery Charging Technology. Figure 9
(**a**) Charging characteristic curve of the modified constant-current technique; (**b**) Current and voltage profiles of the battery during the charging process



Batteries, Battery Management, and Battery Charging Technology. Figure 10
(**a**) Charging characteristic curve of the modified taper characteristic technique; (**b**) Current and voltage profiles of the battery during the charging

where $c > c'$. Figure 10b depicts current and voltage profiles of the battery during the charging time interval.

Enhanced charging performance and prolonged battery life can be achieved using this technique. The main disadvantages of this technique are implementation complexity and using two sensors (current and voltage sensors).

Qualitative Comparison Between Different Charging Techniques Table 1 summarizes different charging techniques and their main properties:

Battery Charging Circuits for Photovoltaic (PV) Systems

Energy storage components are an essential part of a stand-alone photovoltaic (PV) system as they store energy during the high radiation hours during the day and supply load during the low-radiation hours and nights. The battery is an effective energy storage technology for a PV systems. Lead-acid batteries are common due to their high energy density, prevalences and low cost. Different structures that can be used to connect the battery stack to the PV panel are presented in the next sections. In all of these structures, a series diode is connected between the PV panel and the battery to protect the battery against short circuit during the low-radiation conditions and nights.

Series Charge Regulators Figure 11 illustrates a typical charge regulator structure which can be used for both series and parallel charging. In series charging, switch S_2 is always open. Switch S_1 disconnects the PV panel from the battery when state of charge (SoC) of

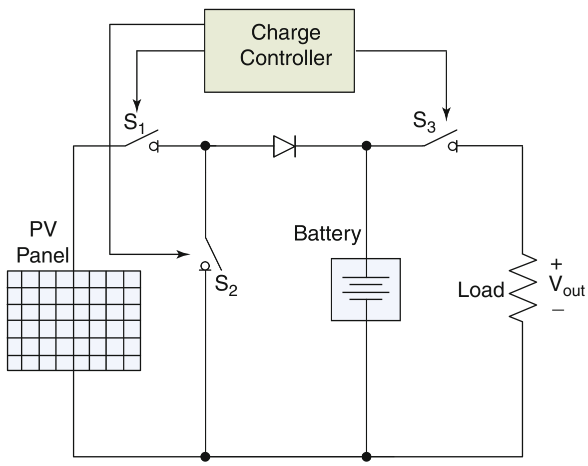
Batteries, Battery Management, and Battery Charging Technology. Table 1 Qualitative comparison between different charging techniques

Charging technique	Advantages	Disadvantages
Constant current (CC)	• Simplicity of implementation • First order open-loop transfer-function • Simplicity of the controller	• Overcharging risk if high charging current is used • Prolonged charging time if low current is used
Constant voltage (CV)	• Simplicity of implementation	• Battery temperature rise during the initial stages of charging • Prolonged charging time due to low current during the final charging stages • Second order open-loop transfer-function
Constant current – constant voltage (CC – CV)	• Protecting the battery against overcharging • No current rush at the beginning stage of charging • Enables float charging after the battery is fully charged • High performance	• Requires both voltage and current sensor for closed-loop control
Pulse current	• Even distribution of ions throughout the electrodes and inside the battery • Prolonged battery life due to maximizing chemical performance • Charging rate can be controlled by the duty cycle of the battery current	• Requires fast control-loop • Requires high bandwidth current-sensor • Expensive
Taper characteristic	• Gradual current decrease during the charging • Protection against overcharging	• Requires both voltage and current sensor for closed-loop control • Complexity of implementation
Assembled constant current	• Eliminates overcharging property of CC charging • Eliminates prolonged charge time property of CC charging • Takes other advantages of CC charging	• More complicated control scheme than CC charging
Assembled taper characteristic	• Different adjustment of characteristic curve is possible to satisfy different design requirements • Enhanced charging performance	• Requires both current and voltage sensors for closed-loop control • Most complex control scheme

battery reaches 100% to protect the battery against overcharging. Switch S_3 disconnects the battery from the load when the battery SoC is less than a predefined value to avoid deep discharging mode, which can degrade the battery and shorten its life. All switches should have very low loss which means they should have very low forward voltage and on-time resistance. Thus, mechanical relays are preferred to fast power semiconductors such as IGBTs with high on-time voltage drops.

Shunt Charge Regulators In a typical shunt charge regulator, the switch S_1 in Fig. 11 is always closed, and switch S_3 operation is similar to series charge regulators to disconnect the load from the battery when battery SoC is less than a predefined value to prevent the battery from deep discharging. Switch S_2shorts the output of the PV panel during low-radiation conditions and nights. When the output of the PV panel is shorted, series diode protects the battery against short circuit condition.

Pulse-Width Modulation Charge Regulators Superior charging functionality can be achieved using pulse-width modulation (PWM) charge regulators. PWM-type charge regulators are able to eliminate external disturbances and can be programmed to follow a specific charging technique that has been discussed in section "Battery Charging Techniques".



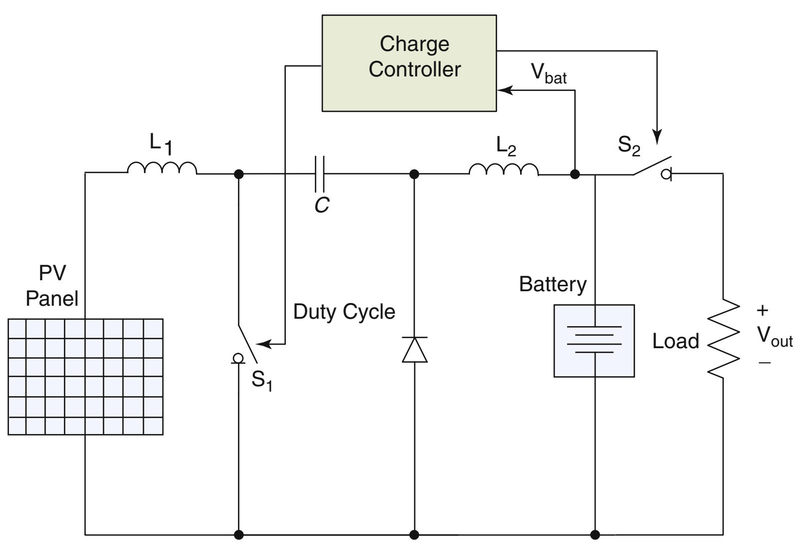
Batteries, Battery Management, and Battery Charging Technology. Figure 11
Circuit diagram of series and shunt PV charging system

Figure 12 shows a buck-boost-type PWM charge controller with voltage and current feedback. The charge controller also has the ability to control switch S_2 to disconnect the load under the condition in which battery SoC is less than a predefined value to protect the battery against deep discharging.

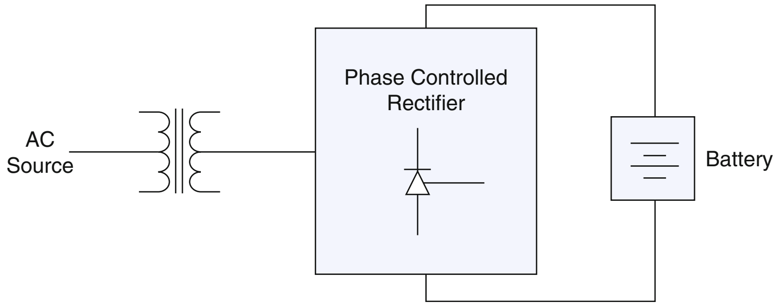
Battery Charging Circuits with AC Sources

Several factors should be considered when designing a charging circuitry with AC input voltage, e.g., nominal output DC voltage, allowable ripple in output current, type of the input AC voltage source (single-phase or three-phase), AC voltage source ratings (voltage and frequency), charger efficiency and power factor, charger current limiting capability, and recharge duration time. In this section, the conventional battery charger's configurations with an AC input source are discussed.

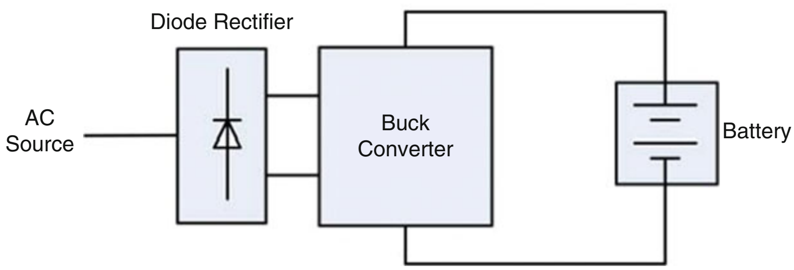
Battery Charger Configurations Given the DC nature of batteries, a rectifier circuit is needed. In a conventional configuration, shown in Fig. 13, a phase-controlled rectifier is adopted. Another configuration is a rectifier bridge in series with a buck DC-DC converter as shown in Fig. 14. If an electrical isolation is required, a DC-DC converter with a high-frequency isolation transformer can be used as shown in Fig. 15.



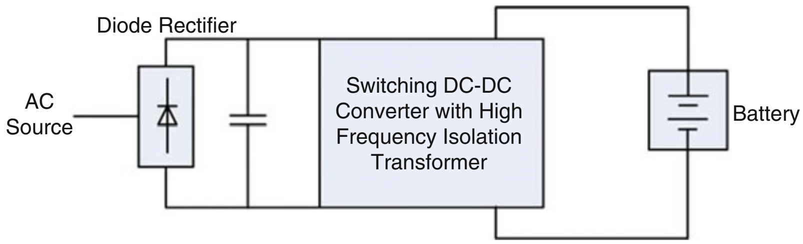
Batteries, Battery Management, and Battery Charging Technology. Figure 12
Circuit diagram of the PWM-PV charging system



Batteries, Battery Management, and Battery Charging Technology. Figure 13
Phase-controlled rectifier



Batteries, Battery Management, and Battery Charging Technology. Figure 14
Rectifier bridge in cascade with a buck converter



Batteries, Battery Management, and Battery Charging Technology. Figure 15
DC-DC converter with a high-frequency isolation transformer

Single-Phase, Phase-Controlled Rectifiers The circuit configuration of a single-phase thyristor-controlled rectifier is illustrated in Fig. 16. The battery is presented as a DC voltage source in series with a resistor (r_d). Considering a continuous battery current, the voltage and current waveforms are illustrated in Fig. 17. Due to the presence of AC side inductance, there is a commutation interval, u. In the continuous mode of battery's current, the approximate average value of the battery voltage is:

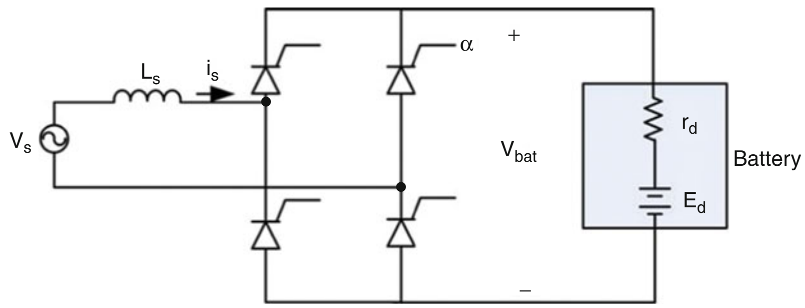
$$V_{\mathrm{bat}} \approx 0.9 V_S \cos\alpha - \frac{2}{\pi}\omega L_S I_{\mathrm{bat,min}} \tag{4}$$

where $I_{\mathrm{bat,min}}$ is the minimum value of battery current which occurs at $t = \frac{\omega}{\alpha}$.

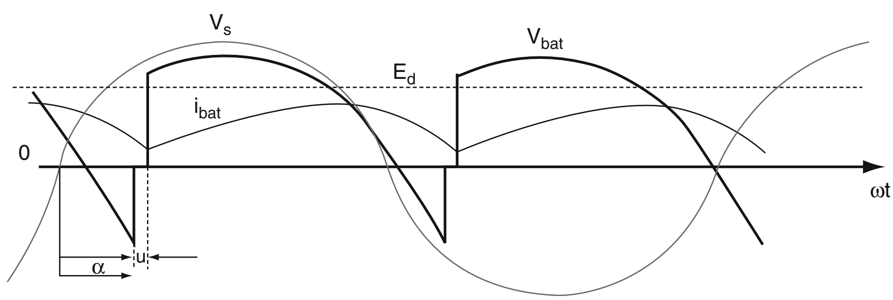
The average value of battery current can be calculated using (5):

$$V_{\mathrm{bat}} = r_d I_{\mathrm{bat}} + E_d. \tag{5}$$

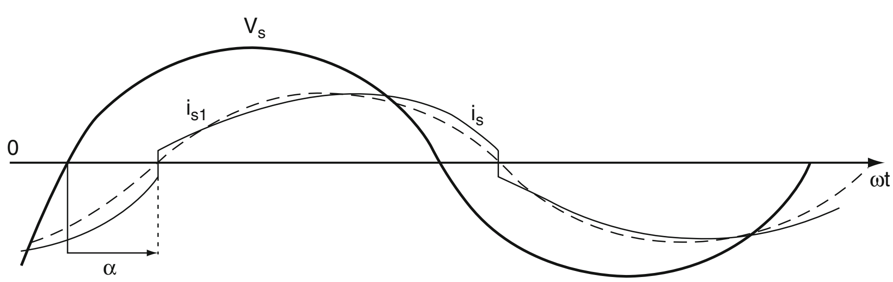
Figure 18 shows the input line current (i_s). Neglecting L_s, AC source current is a square wave



Batteries, Battery Management, and Battery Charging Technology. Figure 16
Single-phase thyristor rectifier



Batteries, Battery Management, and Battery Charging Technology. Figure 17
Battery's voltage and current waveforms



Batteries, Battery Management, and Battery Charging Technology. Figure 18
Input line current

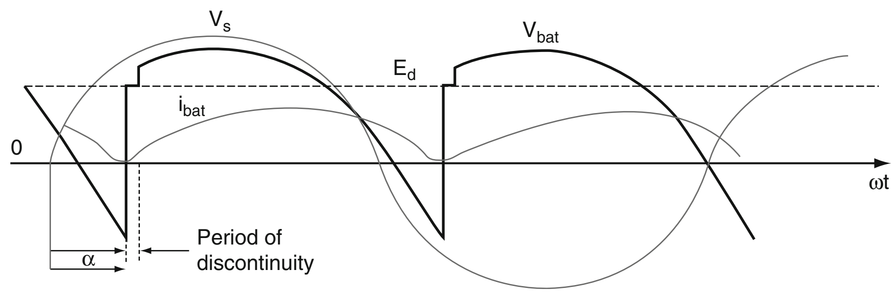
current with only odd harmonics. These harmonics can be expressed as (6):

$$I_{sh} = \frac{I_{s1}}{h} \tag{6}$$

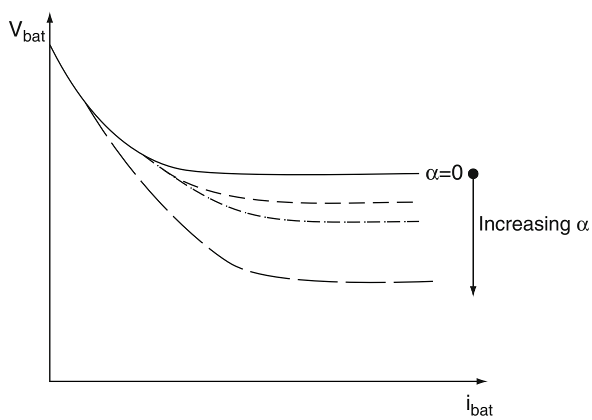
where I_{s1} is the RMS value of the fundamental frequency of I_s. The total harmonic distortion of input line current in a single-phase configuration is around 48.43%. The power factor of the single-phase configuration is expressed in (7):

$$PF = 0.9 \cos \alpha. \tag{7}$$

At low values of i_{bat}, the battery current waveform may become discontinuous as shown in Fig. 19. Through the appropriate choice of firing angle α, one can control the average value of battery voltage and



Batteries, Battery Management, and Battery Charging Technology. Figure 19
Battery voltage and current in discontinuous mode of operation



Batteries, Battery Management, and Battery Charging Technology. Figure 20
Rectifier output profile for different values of α

thus battery current and, therefore, the power delivered. Figure 20 shows the variations of V_{bat} versus i_{bat} for different values of α. For a given value of α, if i_{bat} becomes less than a specific threshold, V_{bat} increases sharply. In such a case, α has to increase to keep V_{bat} constant.

Three-Phase, Phase-Controlled Rectifiers Figure 21 shows the circuit configuration of a three-phase phase-controlled rectifier connected to a battery. Similar to the single-phase configuration, the battery is presented as a DC voltage source in series with a resistor (r_d). Assuming a continuous current for battery, battery's voltage waveform is illustrated in Fig. 22. In this figure, u and α present the commutation interval and delay angle, respectively. The average value of battery voltage can be expressed in terms of (8). Compared with the single-phase configuration, the ripple in the output voltage of three-phase rectifier is less:

$$V_{\text{bat}} \approx \frac{3\sqrt{2}}{\pi} V_{\text{LL}} \cos\alpha - \frac{3}{\pi}\omega L_{\text{S}} I_{\text{bat}} \tag{8}$$

where V_{LL} is the RMS value of the line voltage of AC source, and I_{bat} is the battery current.

Figure 23 shows the input line current of phase "a" (i_{S}). Neglecting L_{S}, AC source current harmonics can be expressed as (9):

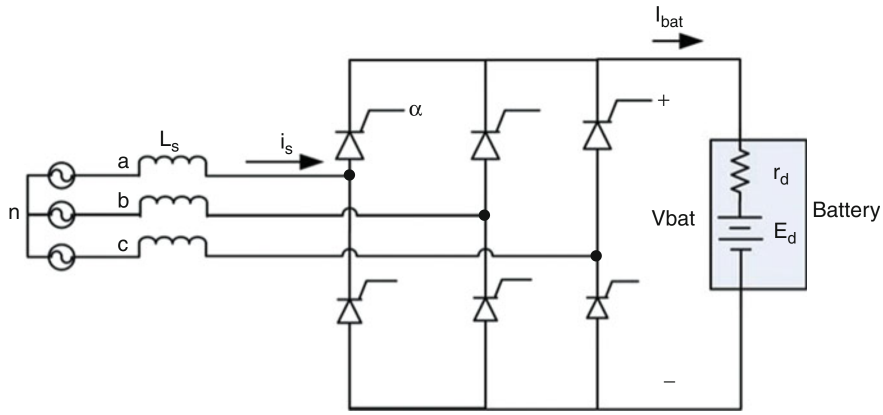
$$I_{\text{sh}} = \frac{I_{\text{s1}}}{h} \quad where\ h = 6n \pm 1 \tag{9}$$

The total harmonic distortion of input line current in three-phase configuration is around 31.08%, less than that of a single-phase configuration. The power factor of three-phase configuration is:

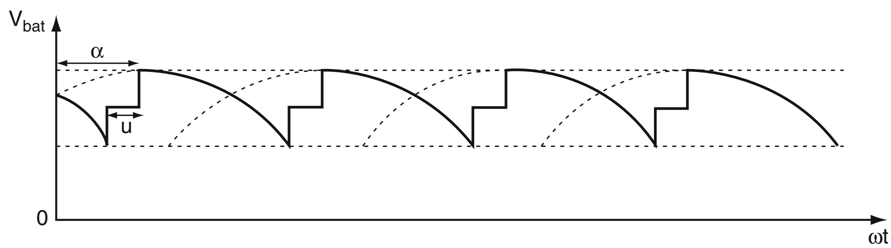
$$PF = \frac{3}{\pi}\cos\alpha. \tag{10}$$

Rectifier Bridge in Cascade with a Buck DC-DC Converter In this configuration a rectifier is in cascade with a buck DC-DC converter. In the buck converter, which is shown in Fig. 24, the average output voltage is lower than DC input voltage. Figure 25 shows the waveforms of V_d, V_{bat}, V_L, and i_L for a resistive load and continuous conduction of inductor. t_{on} denotes the time that the switch is on in a switching period. Because of the fact that the integral of the inductor voltage should be zero over a time period, the output voltage is:

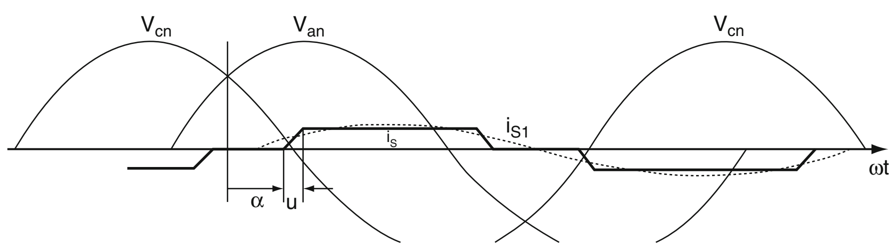
$$\frac{V_{\text{bat}}}{V_{\text{in}}} = \frac{t_{\text{on}}}{T_s} = D. \tag{11}$$



Batteries, Battery Management, and Battery Charging Technology. Figure 21
Three-phase phase-controlled rectifier



Batteries, Battery Management, and Battery Charging Technology. Figure 22
Battery's voltage waveform

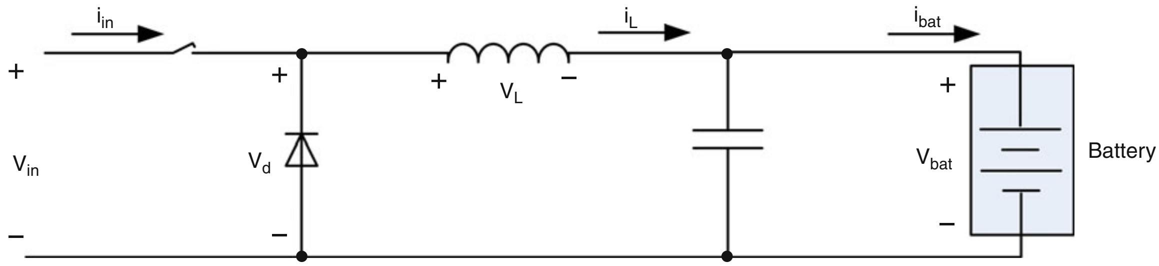


Batteries, Battery Management, and Battery Charging Technology. Figure 23
Input line current

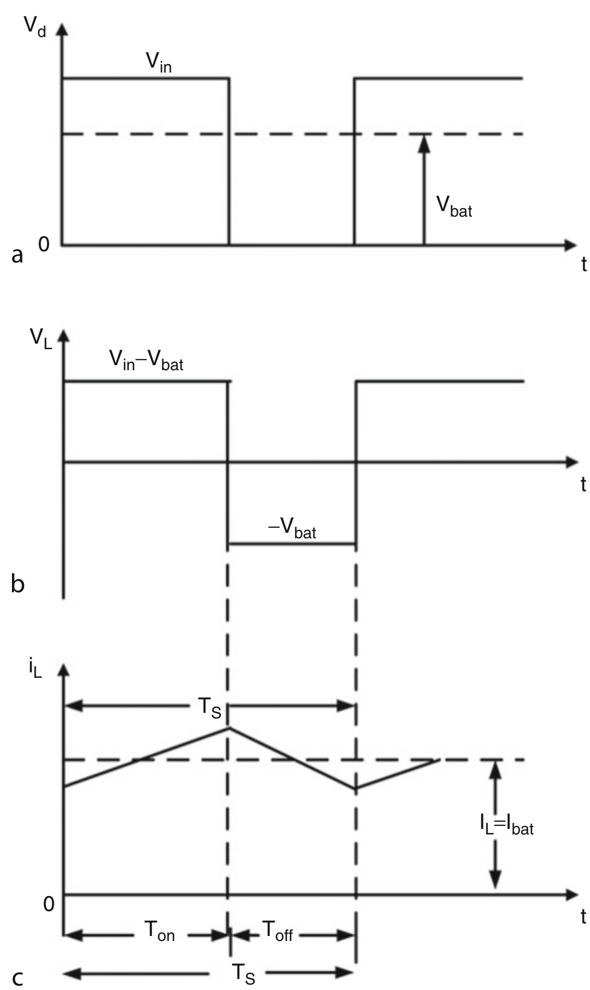
Ignoring losses, the expression for output current is:

$$\frac{I_{\mathrm{bat}}}{I_{\mathrm{in}}} = \frac{V_{\mathrm{in}}}{V_{\mathrm{bat}}} = \frac{1}{D}. \tag{12}$$

DC-DC Converter with a High Frequency Isolation Transformer In this configuration using a diode rectifier, the input AC voltage is rectified into a primary DC voltage. Using high-frequency switching, the primary DC voltage is converted from one DC level to another. This task is done by using a high-frequency transformer. The output of this configuration is controlled by adopting a PWM feedback control. Figure 26 shows the simplified block diagram of this configuration with its control system. Flyback, forward, push-pull, half bridge, and full bridge are the main types of this battery configuration.



Batteries, Battery Management, and Battery Charging Technology. Figure 24
Buck converter



Batteries, Battery Management, and Battery Charging Technology. Figure 25
(**a**) Diode voltage; (**b**) Inductance voltage; (**c**) Inductance current

Flyback Converter Figure 27 shows the circuit topology of this converter. This converter is derived from buck-boost converter. Defining the switch duty ratio D as the ratio of the time the switch is on t_{on} to the total switching period T_s, $D = \frac{t_{on}}{T_s}$, the DC output voltage is:

$$\frac{V_{bat}}{V_{in}} = \frac{N_2}{N_1}\frac{D}{1-D}. \tag{13}$$

Forward Converter Figure 28 shows the circuit topology of this converter. This converter is derived from a step-down (buck) converter. The expression for the DC output voltage level is:

$$\frac{V_{bat}}{V_{in}} = \frac{N_2}{N_1}D. \tag{14}$$

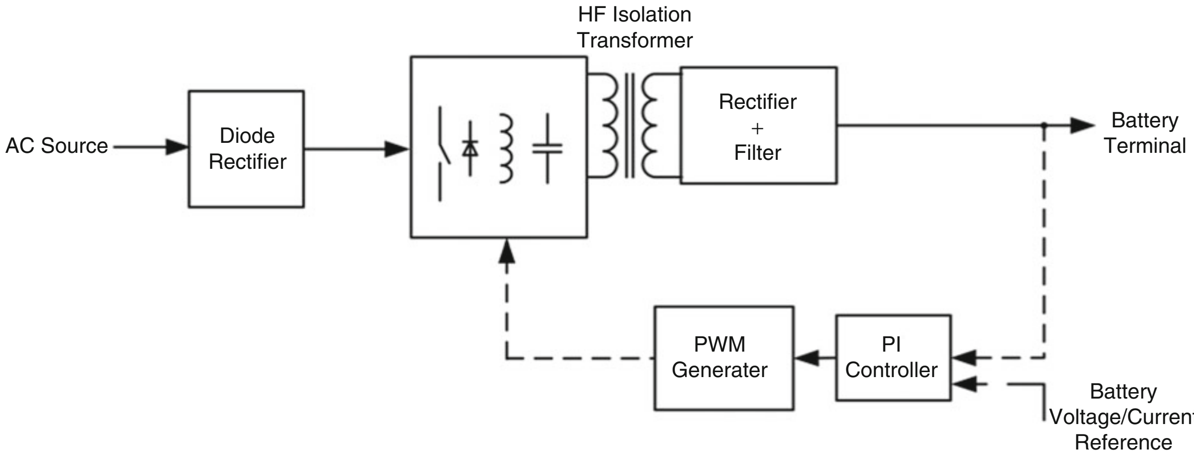
Push-Pull Converter Similar to forward converters, push-pull converters also have the same operation as buck converters. Circuit configuration of these converters is shown in Fig. 29. The expression for the DC output voltage level is:

$$\frac{V_{bat}}{V_{in}} = 2\frac{N_2}{N_1}D\,, \quad 0 < D < 0.5. \tag{15}$$

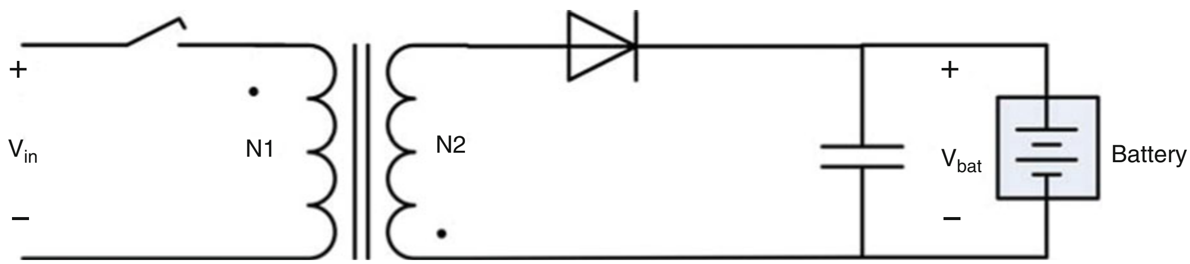
In practice, in order to avoid simultaneous conduction of both switches, D should be less than 0.5.

Half-Bridge Converter Figure 30 shows the circuit configuration of this converter. This converter is also derived from step-down converters. The expression for the DC output voltage level is:

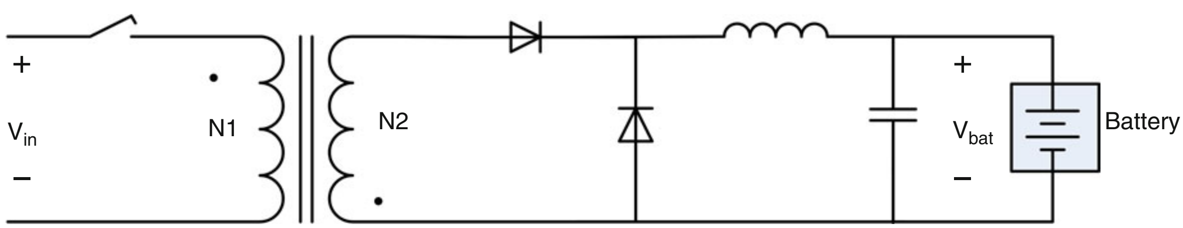
$$\frac{V_{bat}}{V_{in}} = \frac{N_2}{N_1}D\,, \quad 0 < D < 0.5. \tag{16}$$



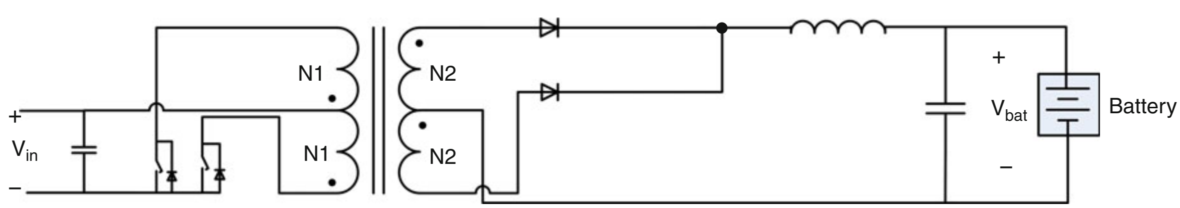
Batteries, Battery Management, and Battery Charging Technology. Figure 26
DC-DC converter with a high-frequency isolation transformer and its control system



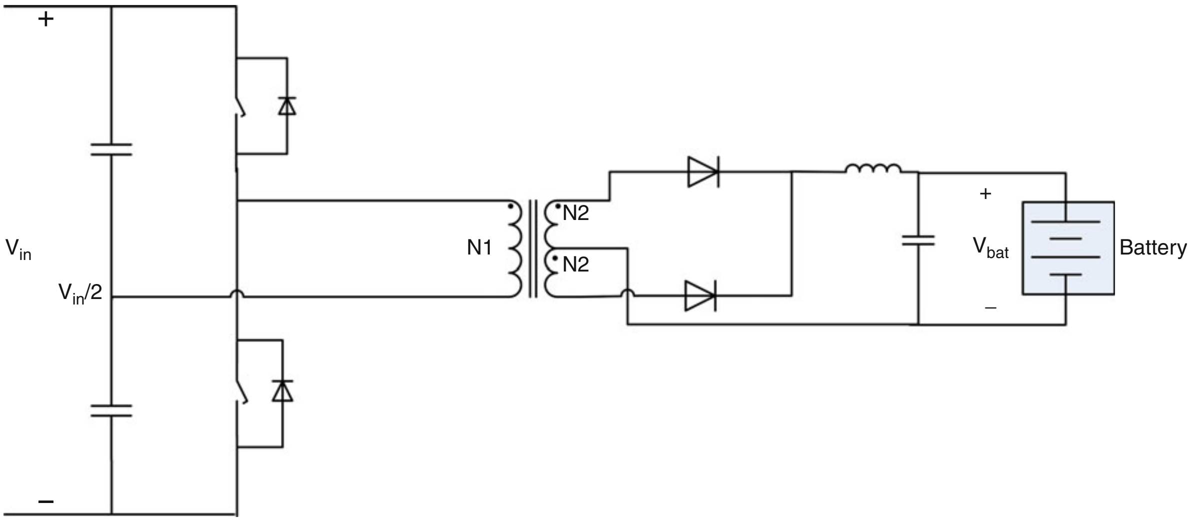
Batteries, Battery Management, and Battery Charging Technology. Figure 27
Flyback converter



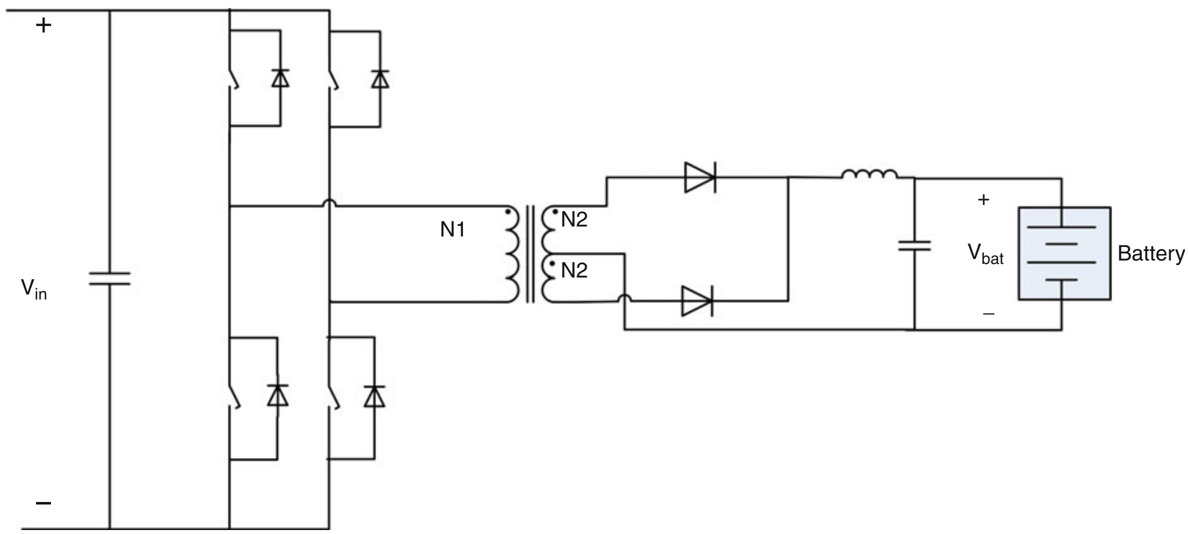
Batteries, Battery Management, and Battery Charging Technology. Figure 28
Forward converter



Batteries, Battery Management, and Battery Charging Technology. Figure 29
Push-pull converter



Batteries, Battery Management, and Battery Charging Technology. Figure 30
Half-bridge converter



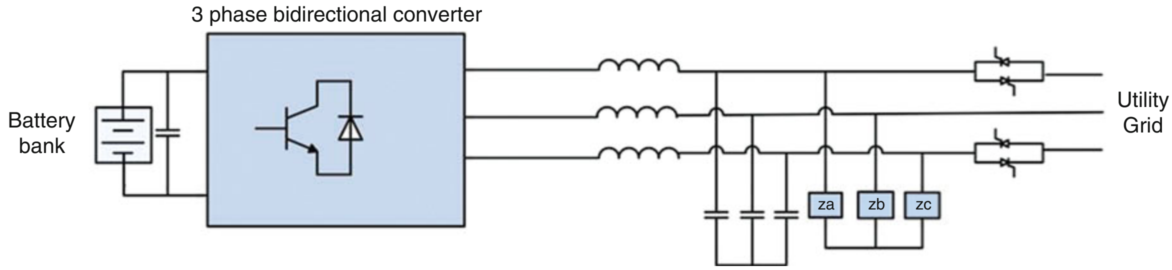
Batteries, Battery Management, and Battery Charging Technology. Figure 31
Full-bridge converter

Full-Bridge Converter Full-bridge converters also have the same operation as buck converters. Their circuit configuration is shown in Fig. 31. The expression for the DC output voltage level is:

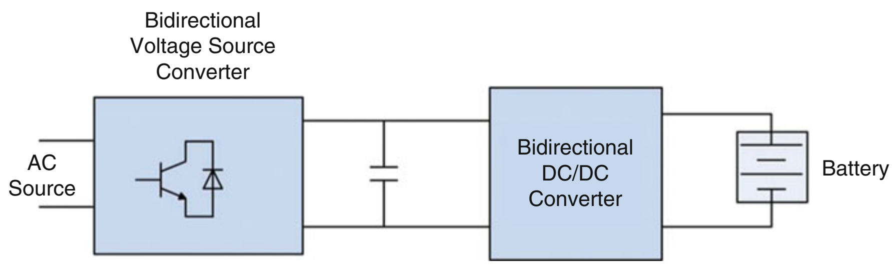
$$\frac{V_{\text{bat}}}{V_{\text{in}}} = 2\frac{N_2}{N_1}D\,, \quad 0 < D < 0.5. \tag{17}$$

Bidirectional Configurations for Battery Charging with AC Sources

Bidirectional configurations for battery charging are used in multifunctional battery energy storage systems (BESS) and plug-in hybrid electric vehicles (PHEV). In the case of BESS, considering normal operation of the



Batteries, Battery Management, and Battery Charging Technology. Figure 32
Bidirectional configuration for BESS



Batteries, Battery Management, and Battery Charging Technology. Figure 33
Bidirectional configuration for PHEV

power system, the battery package can be charged and BESS can be controlled to shave the pick load. In the power failure condition, the battery pack is discharged and BESS provides an uninterruptible power for the utility grid. Figure 32 shows a three-phase configuration of a BESS system. Sophisticated control systems provide required commands for the switching system of the bidirectional converter which is a current-forced sinusoidal pulse-width modulated switching.

In the case of PHEVs, the battery pack should have this capability to store energy from an external power source and regenerative braking as well as sending back the stored energy to the utility grid. Figure 33 shows the PHEV battery charger configuration. This battery charger consists of a bidirectional AC-DC converter in cascade with a bidirectional DC-DC converter.

Contactless Battery Charging

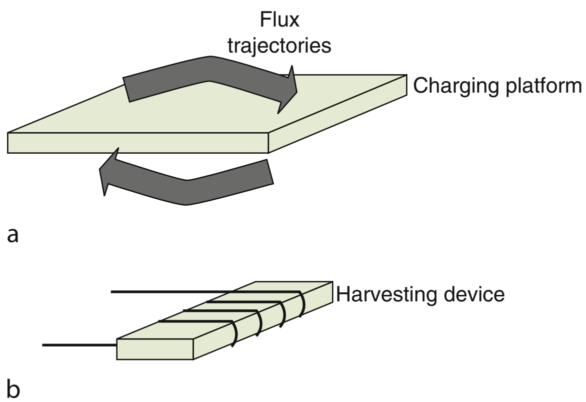
In recent years, a new approach for battery charging, named contactless battery charging, has emerged. This new charging scheme alleviates the wiring requirements and provides an easy charging process for cell phones, laptops, cameras, PHEVs, etc. Currently, there are two dominant technologies for contactless battery charging named inductive contactless battery charging and capacitive contactless battery charging.

Inductive Contactless Battery Charging The planar contactless battery charging platform is the predominant technology for contactless chargers. It uses inductive interface between energy transmitter and energy receiver and has the potential to unify all battery charging protocols related to portable electronic devices such as cell phones, music players, etc. Generally, there are two main schemes for implementing inductive contactless battery charging. The first scheme adopts horizontal flux in which magnetic flux moves horizontally onto the planar charging surface and flows on both sides of the planar. To achieve this requirement, a thick layer of soft magnetic material such as ferrite or amorphous alloy as the flux guide is used. Figure 34a shows the charging platform with horizontal magnetic flux trajectories. Figure 34b shows the secondary harvesting device which should pick up the fluxes from the surface

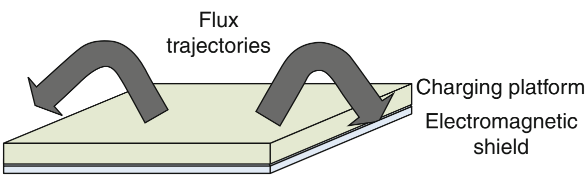
of the charging platform. This energy-harvesting device consists of a magnetic core and a winding and is mounted into the portable electronic device. The cross-sectional area of this device should be large enough to collect enough flux and energy.

The second scheme adopts perpendicular flux in which magnetic flux has a perpendicular trajectory flow to the charging platform surface. The magnetic flux has uniform magnitude over the charging platform. This perpendicular flux trajectory allows a slim energy harvester device which is mounted into the portable electronic device. Figure 35 shows the charging platform with perpendicular magnetic flux trajectories.

Figure 36 shows the block diagram of an inductive contactless charger. The harvested energy is rectified, limited, and regulated to generate a DC voltage across the battery's terminals. Under and over discharge protection, setting of the battery voltage and current profiles, and implementing battery charging control techniques can be achieved by using an appropriate control system. Conventional configurations for battery charging circuits, explained before, can be used for the battery charger.

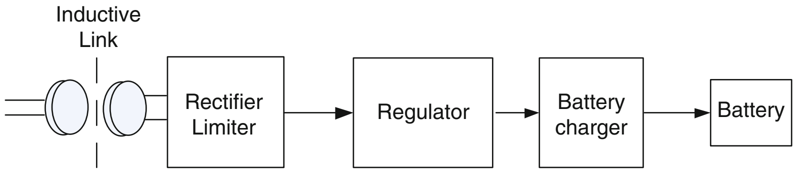


Batteries, Battery Management, and Battery Charging Technology. Figure 34
(**a**) Charging platform with horizontal magnetic flux trajectories; (**b**) Energy-harvesting device



Batteries, Battery Management, and Battery Charging Technology. Figure 35
Charging platform with perpendicular magnetic flux trajectories

Capacitive Contactless Charger Thick electromagnetic flux guide is an important requirement in implementing efficient inductive contactless chargers. The confined electric field between conductive plates can alleviate this requirement in capacitive contactless chargers, as shown in Fig. 37. Figure 38 shows the circuit configuration of a capacitive contactless charger based on a series resonant architecture. Two coupling capacitors transfer power from V_{in} to battery. Considering a DC power supply, using an inverter, the input DC voltage is converted to an AC output voltage to enable current flow through the coupling capacitors. This inverter is not required if supplied from an AC source. Inductors are used to enable soft switching. At the final stage, a diode rectifier provides the required DC voltage for battery charging. The circuit parameters should be designed in such a way that a circuit with the least possible value of capacitor and the desired efficiency is achieved.

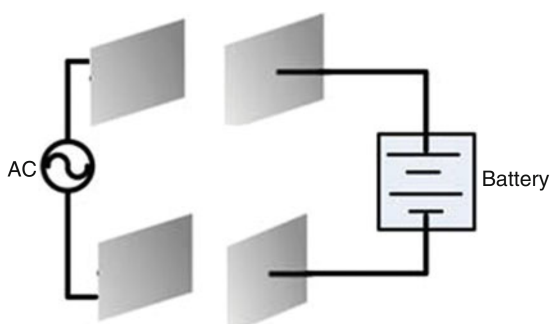


Batteries, Battery Management, and Battery Charging Technology. Figure 36
Inductive contactless charger scheme

Electromagnetic Interference (EMI)

Electromagnetic interference (EMI) is defined as degradation in performance of an electronic system caused by electromagnetic disturbances. Electromagnetic compatibility (EMC) is the ability of that system to operate satisfactorily in an electromagnetic environment without introducing intolerable electromagnetic disturbances to other devices in that environment. Battery charging circuits are power electronic converters in nature. Therefore, EMC rules and regulations exist that apply to the battery charger circuits. Power electronic converters must emit electromagnetic disturbances below the maximum permitted amount (emission) and be able to operate properly when exposed to electromagnetic disturbances below the maximum permitted amount (susceptibility).

There are four types of electromagnetic disturbances: conductive noise, inductive coupling, capacitive coupling, and radiation.



Batteries, Battery Management, and Battery Charging Technology. Figure 37
Capacitive contactless power transferring

Conductive Noise Conductive noise addresses disturbances introduced by coupling of two or more circuits through interconnecting wires. For example, when a utility transformer supplies a rectifier, it is exposed to the same current as of the rectifier. Therefore, if the input current of the rectifier has harmonic content that is intolerable for the transformer, it can cause the transformer to malfunction.

Inductive Coupling Inductive coupling refers to disturbances that are caused by unwanted coupling of windings in different circuits. Leaking flux of an inductor inside a circuit may encircle a winding or a closed path in another circuit and results in inductive coupling. Figure 39 illustrates the modeling circuit of inductive coupling. Mutual inductance, M, indicates the degree to which two circuits are coupled. The winding voltage set is denoted in (18):

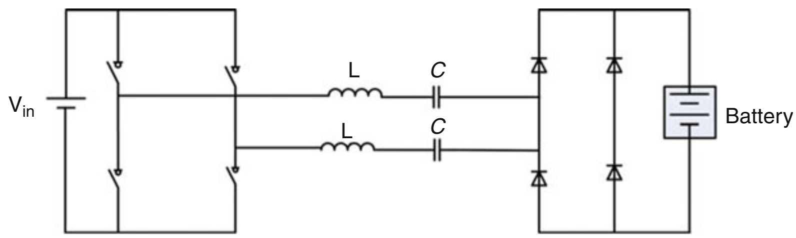
$$\begin{cases} v_1 = L_1 \dfrac{di_1}{dt} + M \dfrac{di_2}{dt} \\ v_2 = M \dfrac{di_1}{dt} + L_2 \dfrac{di_2}{dt} \end{cases} \tag{18}$$

The noise is represented as a mutual term using the mutual inductance

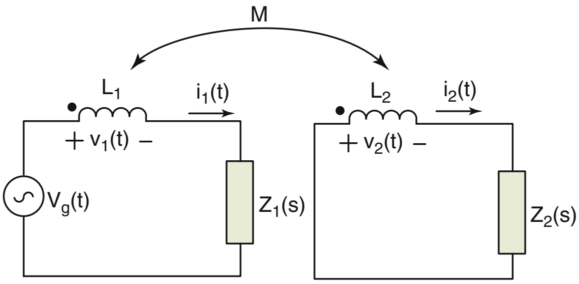
$$v_{\text{noise},12} = M \frac{di_2}{dt}. \tag{19}$$

Capacitive Coupling Figure 40 portrays the capacitive coupling circuit. Capacitive coupling happens when there is a small capacitance between different parts of different circuits, and the medium is electric field. The disturbance voltage caused by V_g can be expressed as:

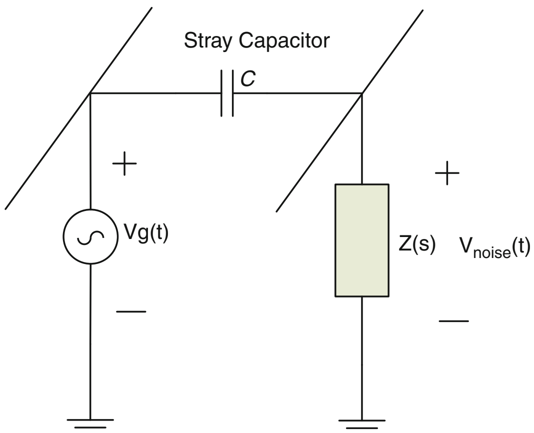
$$V_{\text{noise}}(s) = \frac{Z(s)Cs}{Z(s)Cs + 1} V_g(s). \tag{20}$$



Batteries, Battery Management, and Battery Charging Technology. Figure 38
Capacitive contactless charger circuit configuration



Batteries, Battery Management, and Battery Charging Technology. Figure 39
Modeling circuit of inductive coupling



Batteries, Battery Management, and Battery Charging Technology. Figure 40
Modeling circuit of capacitive coupling

Thus, decreasing *C* reduces the magnitude of induced noise voltage.

Radiation Radiation disturbance is caused by the absorption of electromagnetic waves where it is not intended. When the circuit dimensions are very small compared to one fourth of the wavelength of an electromagnetic wave, that electromagnetic wave cannot be fully absorbed by the circuit. Thus, radiation disturbance usually occurs in high-frequency waves with shorter wavelengths.

EMC in Battery Charging Circuits

Different guidelines should be followed in battery charging circuits to reduce electromagnetic susceptibility and emission of the converter circuit. Radiation disturbance is trivial in power electronic converters because switching frequency is relatively low, which means that the wavelength of the electromagnetic wave is much longer than the circuit dimensions. Susceptibility of the converter to capacitive and inductive noises can be diminished by shielding the converter. Air core inductors should be avoided in the converter circuit to meet electromagnetic interference (EMI) and electromagnetic compatibility (EMC) emission requirements. Using air core inductors causes long flux paths through the air that can encircle other windings and cause inductive coupling. On the other hand, using magnetic core inductors defines a specific path for flux through the core and prevents inductive coupling. The most challenging EMC issue of the power electronic converters is conductive noises. As discussed in the previous sections, battery charging circuits are mainly AC-DC or DC-DC circuits. In DC-DC battery charging circuits, pulsating input current should be prevented to meet EMC emission requirements. Thus, buck and buck-boost converters are not suitable candidates. As an alternative, Boost, Ćuk, and SEPIC converters can be used as they have built-in input current filters. The most suitable choice is a Ćuk converter as it has output current filter that makes it perfect for constant-current charging applications. There are two types of AC-DC battery charging circuits, namely phase-controlled rectifiers and PWM rectifiers. Phase-controlled rectifiers draw square shape input currents that have a very high harmonic content. Thus, the designed input current filter for phase-controlled rectifiers should have lower cutoff frequencies which requires larger and bulkier filter components. On the other hand, the input current of PWM rectifiers has less harmonic content that are located at higher frequencies. This characteristic of the PWM converters enables one to design input current filters by smaller inductors.

Regulations and Standards

Several standards have been developed by different institutes to regulate electromagnetic emission and susceptibility of electrical equipment, namely: MIL-STD 461; IEEE/ANSI SA-C63.14; IEEE 519, IEC 555-2, FCC, title 47, part 15; German VDE; and Japanese standards.

MIL-STD 461 establishes requirements for control of EMI emission and susceptibility of electronic and

electromechanical equipment which are produced for use by agencies of the Department of Defense.

IEEE/ANSI SA-C63.14 provides the definitions for specific terms that are related to EMC, electromagnetic pulse (EMP), and electrostatic discharge (ESD).

IEEE-519 regulates the injection of harmonic currents to the power system due to nonlinear loads such as static power converters, arc discharge devices, saturated magnetic devices, and, to a lesser degree, rotating machines.

The IEC 555-2, IEC 1000-3-2, and IEC 1000-3-4 are emission standard related to operation of power electronic converter. These standards usually set an upper limit for harmonic content in each frequency.

Battery Management

Need for Battery Management

Two critical parameters for battery performance are battery voltage and operating temperature. A battery usually consists of a pack of cells connected in series. Manufacturing processes lead to imperfections in cells, as a result of which, all the cells in a pack are not identical. Electrical imbalances occur during charging and discharging of battery packs. Some cells in a battery will have different voltage levels for the same charging. This mismatch needs to be monitored to improve efficiency and safety of battery pack. Higher than rated temperatures in the batteries lead to undesirable chemical effects. Self-sustaining internal temperature buildup and gas pressure buildup are common. These conditions lead to safety hazards. It is vital to have a mechanism to monitor cell temperature and voltage and keep them within limits.

The main role of battery management systems (BMS) is to monitor cell voltage/current, state of charge/state of health, and the internal battery temperature and ambient temperature. The monitoring circuitry provides signals to the protection unit as well. Battery management systems differ on the basis of their primary functions, which depend upon the intended application. BMS for standby batteries in a power plant deal with monitoring of various battery parameters, maintaining readiness to deliver full power in the event of a system failure, and ensuring equal charging to increase battery life. On the other hand, a BMS in an electric vehicle must communicate with other controls in the automobile such as temperature controls, engine management, and safety systems.

There are three main objectives common to all battery management systems:

- Protect the cells or the battery from damage.
- Prolong battery life via smart control.
- Maintain battery in a state in which it can fulfill the functional requirements of the application for which it was specified.

State of Health Measurement

The state of health is a "measurement" that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It takes into account such factors as charge acceptance, internal resistance, voltage, and self-discharge.

It is an estimate rather than a measurement. Battery manufacturers do not specify the SoH because they only supply new batteries. The SoH only applies to batteries after they have started their aging process either on the shelf or once they have entered service. The SoH definitions are therefore specified by test equipment manufacturers or by the user.

Any parameter which changes significantly with age, such as cell impedance or conductance, can be used as a basis for providing an indication of the SoH of the cell. Changes to these parameters will normally signify that other changes have occurred which may be of more importance to the user. These could be changes to the external battery performance such as the loss of rated capacity or increased temperature rise during operation, or internal changes such as corrosion.

Methods of Determining the State of Charge

State of charge (SoC) is defined as the capacity left in a battery expressed as a percentage of some reference. SoC of a battery is usually expressed as a percentage of the current battery capacity when it is fully charged. This definition may lead to an erroneous result when applied to a battery that has been in service for a long time. The maximum capacity of a battery reduces significantly with prolonged use. Considering this value to be the reference for state of charge measurement can lead to false results.

There are several techniques to determine SoC. A majority of them depend on measuring some convenient parameter which varies with the state of charge. Some are specific to particular cell chemistry. Some of the important ones are listed below:

Specific Gravity Measurement In lead-acid batteries, the electrolyte (sulfuric acid) is used up as the battery is subjected to a discharge cycle. As more and more electrolyte is used up, the specific density of sulfuric acid reduces. Thus, the specific gravity of the sulfuric acid is an indication of the state of charge for lead-acid batteries. This method is not feasible for VRLA batteries.

Voltage Measurement Cell voltage typically decreases for most cells during a discharge cycle. There is an almost linear relation between the state of charge and cell terminal voltage. Results may vary depending upon cell terminal voltage, temperature, discharge rate, and age of cell. A compensation factor needs to be included for SoC calculation by this method.

Li-ion cells have a flat voltage profile during a discharge cycle. The cell voltage drops abruptly when they are close to a complete discharge. As the cell voltage variation with SoC is not linear, cell voltage cannot be selected as a parameter to indicate SoC of Li-ion cells. In general, the voltage measurement technique fails for cells which have a flat voltage profile during a discharge cycle.

Current-Based SoC Estimation Charge in or out of the cell is calculated by integrating the current delivered by the cell for certain duration. This charge is compared with the charge contained by a fully charged cell. This method provides a high accuracy for SoC measurement as it measures the charge directly. Three popular current sensing methods are used.

- Current shunt: The simplest method of determining discharge current is by measuring the voltage drop across a low ohmic value, high precision, series, sensing resistor. This resistor, connected between the battery and the load, is called a current shunt. This method of measuring current causes a slight power loss in the current path and also heats up the battery and is inaccurate for low currents.
- Hall-effect transducers: The Hall-effect transducers avoid the power loss problem, but they are more expensive. Unfortunately, they do not tolerate high currents and are susceptible to noise.
- Giant magneto resistance (GMR) sensors: These sensors are even more expensive than Hall-effect transducers, but they have higher sensitivity. They also have better high temperature stability than Hall-effect devices.

Kalman Filter Technique A Kalman filter is an algorithm to estimate the inner states of any dynamic system. The cell is represented by a mathematical state-space model, and SoC is considered as a state of the system. The Kalman filter accurately estimates the value of SoC and uncertainty. Armed with this information, the battery pack can be subjected to a more complete use, without fear of over- or under-charging cells. Nonlinear models of cells provide a highly accurate result.

The Kalman filter model for a rechargeable battery used in automobiles is initialized with a priori state estimate when the vehicle is turned on. The priori state estimate is provided on the basis of open-circuit voltage readings and a look-up table, self-discharge rate data from the cell model and the prior SoC when the vehicle was turned off. The algorithm then repeatedly updates the state estimate and state-uncertainty (error bound) estimate with each set of new measurements, as the system runs. Laboratory tests on real cells have shown that excellent SoC estimation with very tight error bounds are obtained whether or not the initial SoC estimate is accurate.

SoC Estimation from Internal Impedance Measurements During charge-discharge cycles, the composition of active chemicals changes in the battery, and this is reflected in the changes to internal impedance of the battery. Plots for variation of internal cell impedance with state of charge may be obtained for different cells. Thus, measuring internal impedance can indirectly provide information about SoC of the cell. However, on the flip side, cell internal impedance is also affected by temperature, which may lead to erroneous measurements.

Cell Balancing

When a battery pack is charged and discharged as a unit, individual cell temperature and internal chemistry characteristics can cause capacity imbalances in the form of voltage variations. Imbalances in cell voltages are caused by differences in cell capacities, internal resistances, chemical degradation, and inter-cell and ambient temperatures during charging and discharging. Any capacity imbalance between the modules can threaten the long-term reliability of the string as overall pack capacity is brought to the upper and lower limits of charge. Imbalances in cell voltages can cause cell overcharging and discharging, decreasing the total storage capacity and lifetime of the unit.

In a battery pack consisting of series connected cells, some cells have a diminished capacity owing to slight differences in manufacturing. When such a battery is subjected to charging cycle, the reduced capacity cells reach full charge earlier than the other cells in the battery, and there is a danger of overcharging these degraded cells. The capacity of the anomalous cells reduces even further with every successive charge/discharge cycle. The cumulative result is a temperature and pressure buildup which paves the way for an early failure of the cell.

Once a cell has failed, the entire battery must be replaced, and the consequences are extremely costly. Replacing individual failed cells does not solve the problem since the characteristics of a fresh cell would be quite different from the aged cells in the chain, and failure would soon occur once more. Some degree of refurbishment is possible by cannibalizing batteries of similar age and usage, but it can never achieve the level of cell matching and reliability that is possible with new cells.

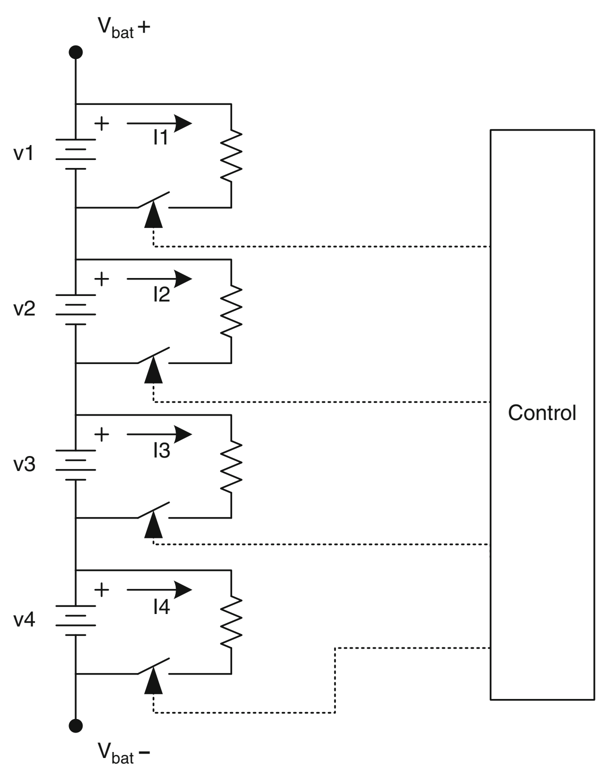
Cell Charge Equalization

Battery management systems (BMS) for charge equalization monitor the state of charge of each cell. In low-cost applications, a circuit to monitor individual cell voltage may be employed. Switching circuits then control the charge applied to each individual cell in the series during the charging process to equalize the charge on all the cells in the pack.

A good charge/discharge equalization technique should ideally have the following features:

- High efficiency: Implementation of this technique should result in minimum power loss of the system.
- Small volume: Bulky volumes restrict portability and increase cost.
- Simple wiring schemes: Complex wiring schemes increase cost and decrease the reliability.
- In automobile applications, the cell must also be equipped to handle pulse charging from regenerative braking.

Passive Balancing Passive-charge balancing techniques involve bleeding off of charge from the cells with the highest voltage (hence, state of charge) in a battery pack (Fig. 41). A cell with a high charge is indicated by its higher cell voltage. Excess energy is removed through a bypass resistor until the voltage or charge matches the voltage on the weaker cells. Some passive balancing schemes stop charging the battery pack at the instant when any one of the cells in the

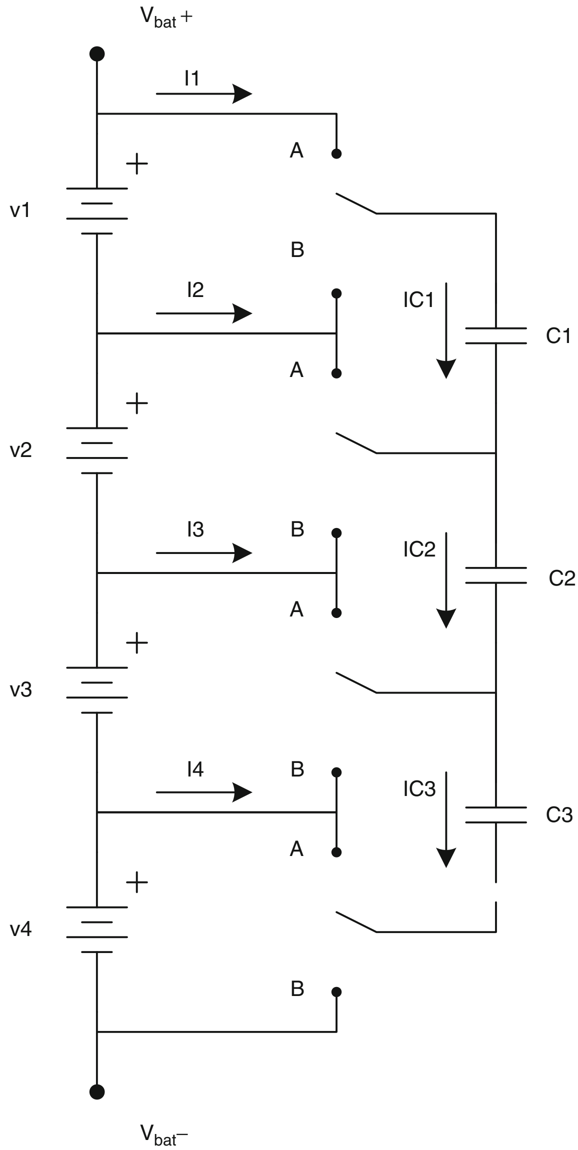


Batteries, Battery Management, and Battery Charging Technology. Figure 41
Passive charge balancing with a dissipative resistor

pack reaches full charge. During discharge operation, they discharge the fully charged cells into a load until these cells reach the same charge level as the weaker cells. These schemes lead to underutilization of the battery pack.

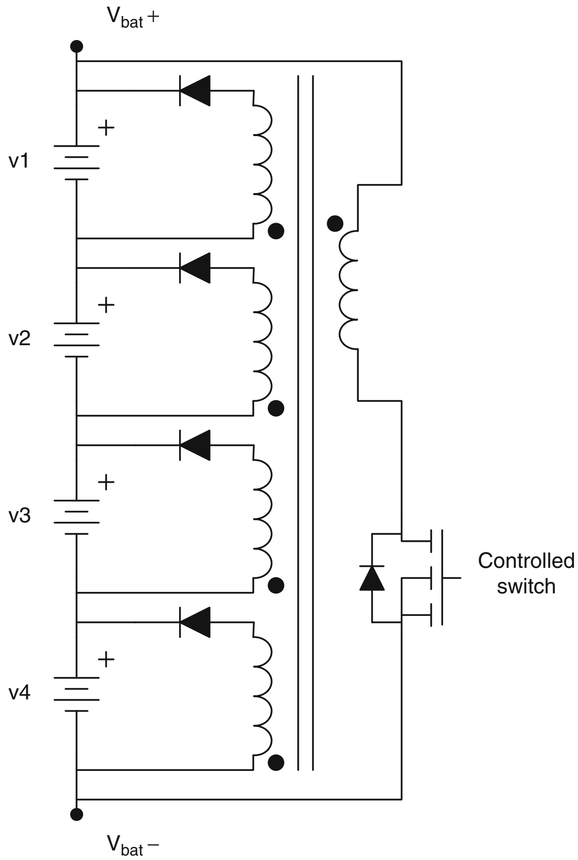
Other schemes are designed to continue charging until all the cells are fully charged but to limit the voltage which can be applied to individual cells and to bypass the cells when this voltage has been reached. The shortcomings of this technique are that this method uses low bypass currents, and hence, equalization times are very long. Also, the battery pack performance is governed by the weakest cell. This process also causes power loss due to the bypass resistors which could drain the battery if operated continuously. It is however very easy to implement and is a low-cost option. Passive balancing is adequate for both lead-acid and nickel-based batteries, incorporating series string up to about six cells. Passive equalization cannot be employed for charge equalization in Li-ion-based battery strings.

Switched Capacitor The switched capacitor charge equalization method, also called a flying capacitor method, uses a capacitor to transfer charge between cells in a battery pack. Typically, these are adjacent cells in the series string as shown in Fig. 42. When the capacitor is connected to a cell with the higher voltage, the capacitor is charged. When the charged capacitor is connected to a cell with a lower voltage, the capacitor discharges and transfers charge into the new cell. When switched between two cells repeatedly, this movement of charge results in current from the cell with higher voltage to the cell with lower voltage. Finally, cell voltages of all cells in the string reach the same value and voltage equalization is achieved. High-frequency switching can be accomplished using a single-pole double-throw switch implemented using two sets of MOSFETs. The MOSFETs are switched with frequencies ranging in several kHz. An important feature in the switching scheme is that switches break before make to prevent momentary short circuits of the respective cells. Accordingly, the switch control signals incorporate a dead-band interval. This method is easy to implement and it results in reduced losses. A major drawback is that equalization process takes a long time if voltage differences between adjacent cells are small.



Batteries, Battery Management, and Battery Charging Technology. Figure 42
Schematic of a switched capacitor equalizer

Multi-Output Transformer This method uses a transformer with its primary winding connected across the battery and one secondary winding which can be switched across individual cells. Both flyback and forward topologies are employed in practice. Figure 43 illustrates a flyback-based circuit to carry out charge balancing for a battery string. In the flyback structure, when the main switch is switched on, some



Batteries, Battery Management, and Battery Charging Technology. Figure 43
A schematic of a flyback-type inductive shuttle charge distribution

energy is stored in the transformer magnetic field. When the switch is turned off, the energy is transferred to the secondary of the transformer, similar to the flyback concept. The bulk of the energy is taken up by cells with lowest cell voltage. The main difference of this method over the switching capacitor scheme is that this method involves taking pulses of energy from the full battery, rather than small charge differences from a single cell, to top up remaining cells. Averaging of the charge level is similar to flying capacitor method, but it avoids the problem of small voltage differences in cell voltage and is consequently much faster. The transformer must have well-balanced secondary windings, otherwise voltage imbalances occur. Also, care must be taken to prevent transformer saturation.

DC-DC Converter Methods This technique involves using power electronics-based converters to transfer energy from higher charged cells to charge-efficient cells in a battery string. Different converter topologies such as the flyback, buck-boost, and Ćuk have been investigated to transfer energy between the batteries. Energy transfer may be unidirectional or bidirectional.

In unidirectional flyback mode, excess energy in the higher charged cell is transferred to the magnetized inductor of the transformer during turn-on operation of the converter. During the turn-off mode, this energy is returned to charge-deficient cells in the battery bank, and thus, charge leveling is achieved. Bidirectional converters are employed to facilitate local energy transfer between two neighboring cells independent of their respective cell voltage. The converters are operated in discontinuous mode to minimize switching losses. The disadvantage is that energy transmission efficiency is low when energy transfer occurs from the first cell to the last with many intermediate stages in a long string. To avoid power loss in intermediate stages, non-isolated buck-boost topologies have been explored in which energy is transferred from the first cell to all other cells in a bank without any intermediary.

Future Direction

Batteries and battery technologies are expected to become even more important in the future as consumers demand longer battery life from consumer electronics; variable energy sources, such as wind and solar, increase in prevalence in the electrical grid; and hybrid and all-electric vehicles become commonplace, to name a few applications currently driving technology development. The emphasis will be to develop batteries with low cost, high energy density, low weight/volume, completely safe, environmentally friendly, easily disposable, and made from abundant raw materials. Auxiliary battery management systems will become increasingly integrated into the battery pack to create a true "plug and power" energy storage module.

Lithium-based cells hold great promise for the future. Lithium-ion cells have nearly proliferated the consumer electronics market. These batteries are also expected to find a prominent role as ideal electrochemical storage systems in renewable energy plants, as well

as power systems for sustainable vehicles, such as hybrid and electric vehicles. However, scaling up the lithium battery technology for these applications is still problematic since issues such as safety, costs, wide operational temperature, and materials availability are yet to be adequately resolved. Safety is an important issue with Li-ion technology, and hence, it forms one of the most important aspects of future research. Lithium-copper cells are seen as the future prospect for lithium-based batteries, although the technology is still in a nascent state. Traditionally, cathodes of Li-based cells have not been reusable and hence the motivation for Li-Cu system which makes provision for reusable electrodes.

Li-air batteries in which oxygen from the air serves as the cathode and lithium as the anode are also being explored and hold promise to increase energy density. Estimates indicated that the lithium-air battery could hold 5–10 times as much energy as a lithium-ion battery of the same weight and double the energy for the same volume. In theory, the energy density could be comparable to that of liquid fuels such as gasoline. However, rechargeable Li-air batteries are still some years away. Flow batteries hold promise for stationary, high-energy applications such as power stations to provide peak loads, backup energy in case of emergencies, and source leveling to mitigate variable production from renewable sources. Zn-Bromine, metal air, vanadium redox are some of the batteries which are being explored for UPS and grid storage applications as an alternative to VRLA batteries, which is currently the standard.

On the battery management side, mobile energy platforms are driving push toward wireless charging technologies and standards for contactless charging. The Wireless Power Consortium has recently developed the standard for contactless charging called "Qi" for low-powered electronic devices (i.e., less than 5 watts). This standard is suitable for cellular phones and contains interface definition, performance requirements, and compliance testing. Further progress is expected for more powerful chargers for higher-power-consumption devices such as laptops. In the future, all compatible devices with the "Qi" standard will carry the "Qi" logo to show compatibility with "Qi" transmitters. The final goal is to have portable electronic devices charged with the stations with "Qi" logo in airports, railway stations, hotels, etc. Currently, the inductive contactless chargers can transmit power in short distance and with the same speed as wired chargers (e.g., cell phone applications). However, capacitive battery chargers can transmit higher levels of power in shorter time frame. Once the associated costs are alleviated, capacitive contactless charges can dominate the market. It has already started in applications such as a camera flash, where the ability to transfer high power over a short period of time is important. Inductive contactless chargers, however, will remain prime candidates for vehicular-charging applications.

Intermittency of renewable energy systems introduces some integration problems especially for high penetration levels of wind and solar energy systems. The battery energy storage systems are expected to play an important role in addressing intermittency. Appropriate control strategies are under development for charging systems to make wind and solar plant hourly dispatched based on forecasted conditions. Bidirectional converters are a key element here; the battery is charged by the grid during low-demand hours or by wind and solar plants during high-irradiance hours and windy periods. The battery is then discharged to the grid during shading of solar panels or lower wind speeds.

Charging circuitry is also used in stations for electric and plug-in hybrid vehicles (EVs and PHEVs). Three standardized charging levels are defined by the National Electric Code for EVs and PHEVs. Level one method uses 120 V, 15 A (12 A usable) power outlets which are common in residential and commercial units in the USA. However, they prolong the charging period due to limited maximum power (about 1.44 kW). Level two chargers use 240 V, single-phase, 40 A, outlets. They are known as the "primary" or "preferred" method of charging for PHEVs. There are two types of level two chargers, namely, inductive and conductive (wired). Although level two chargers enable faster charging, they require more safety restriction. Level three chargers use 480 V, 60–150 kW, three-phase power lines. They are intended to charge battery in about 10–15 min, also known as "fast charging" method. One may argue that PHEV batteries can be charged in 1–2 h using level two chargers, and thus, there are less incentives for higher power level three chargers in charging infrastructure for PHEVs.

Integrated battery chargers are an important aspect when considering system-on-chip devices. System-on-chip devices combine different parts of a system, which may conventionally require their own chip, into a single chip. For example, a typical system-on-chip sensor is designed to sense and transmit the data from an inaccessible location to the main controller. It is comprised of an integrated sensor, analog-to-digital converter, micro-controller, memory, and RF transmitter. Usually these system-on-chip sensors must be autonomous systems and thus generate their own power for an extended period of time. The required power for these micro-sensors can be supplied by solar cells or piezoelectric materials. Given the intermittency in the output of solar cell, micro-batteries are required to power the system during the low-light conditions. Therefore, integrated battery charging circuits are one of the essential components of system-on-chip sensors. Integrated battery chargers must meet specific criteria, namely, high efficiency, simple structure, and, most importantly, small size. Size is the prevalent factor in determining the total cost of the system in system-on-chip application. Therefore, in the applications that require extreme integration and low cost, battery is also integrated in the chip together with charger circuit.

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Battery Technologies

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Article Outline

Definition of the Subject

The demand for high performance and long life storage systems has lead to numerous research initiatives, aimed at the development of such systems. Developmental paths are aligned with the requirements of the applications of these systems. A detailed understanding of technical characteristics and cost considerations is provided in this paper for various battery chemistries: contemporary, vintage, and prospective. A clear understanding of battery characteristics is essential for guiding the selection of such batteries. Indeed, because of the critical functions fulfilled by batteries as well as the substantial costs of advanced batteries, a realistic appraisal of candidate battery performance and costs against requirements is key to judging the prospects of new applications such as EV, HEV, and plug-in hybrid electric vehicles (PHEV). Although electric vehicles (EVs) have been around since before 1900 the limitations of the batteries to drive them have not enabled them to compete in the general consumer's market with the internal combustion engine. Automotive parts are limited by space and weight. Therefore EVs and hybrid electric vehicles (HEVs) require a battery with high energy density. Specific energy is defined as the energy per kilogram of the battery while energy density is the energy per unit volume. Early designs (1990–1995) of lithium-ion batteries only had a specific energy of 0.2 kWh/kg. EVs also require a battery with high power output for large power draw, such as quick acceleration. The General Motors EV1 had a battery pack weighing almost 600 kg while the car weighed 1,350 kg. The battery would then account for more than 44% of the car's weight. A marked improvement in energy cell density of batteries was required for practical EVs.

Introduction

In this paper, the first section covers the relationship between the internal resistance of the cell, maximum power output, energy efficiency in charging and discharging, and reduction of cell heating. This is followed by a review of the characteristics of lead acid, nickel metal hydride, lithium-ion batteries, and supercapacitors.

Recent advances in power electronics provide competitive performance for electric cars so they provide the necessary acceleration for wide spread adoption [1]. However batteries still lack the energy density of gasoline or diesel fuels and thus cannot compete in terms of the overall range that can be driven between recharging. Additionally, recharging may be slow. However, ongoing research and improvements in manufacturing may reduce both energy density limitations and costs. Concerns about greenhouse gases and other air pollutants are the other driving factors for the renewed interest in EVs and HEVs, which may reduce or eliminate the emission of NO_x, CO_2, and hydrocarbon pollution from mobile vehicles depending on how the electricity used to charge the battery was generated. EVs and HEVs also reduce noise levels when running on electric mode. In 2009, 1.6 million HEVs were registered in the USA [2].

This section concentrates on a variety of battery technologies that have shown significant promise for

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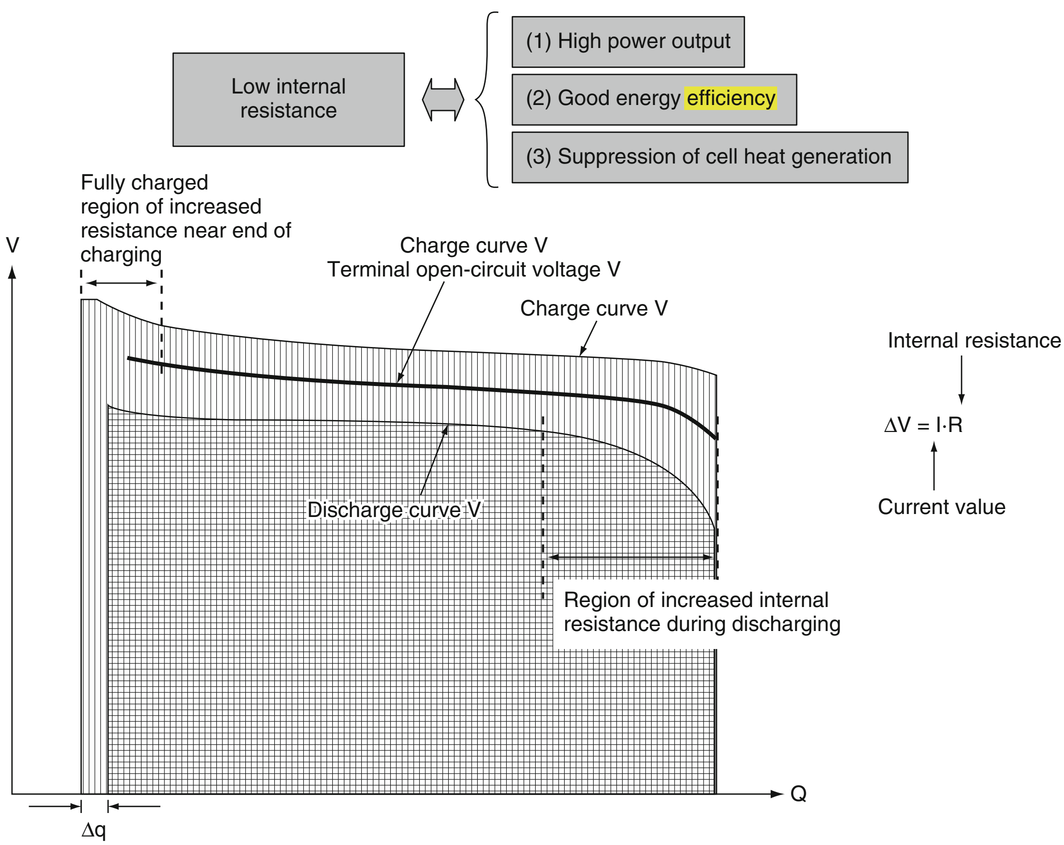
long life and high performance. A brief, generic list of battery characteristics are provided in section "Electrical Modeling for Batteries". Section "Lead Acid Batteries" introduces various types of lead acid battery chemistries. Section "Nickel Metal Hydride Battery" introduces the nickel metal hydride chemistry, while lithium-ion is discussed in section "Lithium-Ion Batteries". The upcoming technology of supercapacitors is also introduced and a comparison to conventional electrochemical counterparts is provided.

This entry first gives a general overview of characteristics of batteries, followed by the electrical modeling used for batteries in EVs and concludes by presenting the different battery technologies used today.

Basic Characteristics of Batteries

An electrical battery is a power source composed of one or more electrochemical cells which convert stored chemical energy into electrical energy. In this section, rechargeable batteries which can be used multiple times is discussed. A battery is composed of one or more electrochemical cells, each consisting of two electrodes and one (or two) electrolyte-containing anions and cations.

Figure 1 depicts the typical electrochemical cell voltage behavior during charging (labeled "Charge curve V") and discharging (labeled "Discharge curve V"). Cell voltage drops and rises during discharging and charging respectively, in proportion to the cell's internal voltage. The difference between the terminal open-circuit voltage



Battery Technologies. Figure 1
Cell voltage profile and internal resistance in charging and discharging operations with respect to cell charge Q [3]

and the discharge and charge voltage is attributed to the cell's internal resistance. An ideal cell provides constant terminal voltage until empty. The internal resistance of real cells prevent ideal performance during discharge resulting in lower terminal voltage.

The essential characteristics of batteries are maximum power output, charging/discharging efficiency, and temperature effects. These are key factors to be considered when designing or choosing batteries for particular applications. These characteristics are further elaborated for each battery in the device specific sections of the paper. The basic definitions are shown below.

Maximum power output: A lower limit is set for each cell's voltage. The maximum dischargeable current value is determined such that the cell voltage does not fall to this limit. The maximum current is determined as

$$I_{max} = (\text{Open Circuit Voltage} - \text{Lower Limit Voltage})/\text{Internal Resistance}$$

Then, maximum power output of a cell can be calculated as $P_{max} = I_{max} \bullet$ (Open Circuit – Lower Limit Voltage). High power output requires low internal cell resistance.

Charging/discharging efficiency: Electrical energy transferred during a charging/discharging cycle can be computed as

$$E = \Delta Q \bullet V$$

where ΔQ is the transferred charge and V is the terminal voltage at that time.

In Fig. 1, the *area* between the charge curve and the horizontal axis is the total electrical energy transferred to the battery. Accordingly, the area between the discharge curve and horizontal curve is the total energy drained from the battery. Battery efficiency is a ratio of discharge to charge energy values. It is imperative to reduce the difference between these two curves to improve battery efficiency.

Temperature effect: Charging and discharging cycles can cause a cell's temperature to rise. For lithium-ion cells, operating temperatures above 50°C can lead to cell degradation. Ozawa [4] attributes the difference in charging and discharging curves in Fig. 1 to heat lost due to different operating temperatures. To suppress this difference, the cell's internal resistance must be reduced.

Electrical Modeling for Batteries

A simple model of a battery can help alleviate issues of understanding of a battery's behavior. The simplest electrical equivalent model of a cell is a voltage source with a resistor in series, as shown in Fig. 2a. This is the internal resistance of the cell. Davide [5] provides corresponding voltage and current response curves for each proposed model.

A more complex model is described in Fig. 2b. This model emulates the behavior of a battery when instantaneously loaded. The initial voltage drop across battery terminals is small, due to R_1. The voltage then drops exponentially to the level of both resistances with a time constant $T = R_2 \bullet C_2$ (~1 min). This phenomenon is known as relaxation.

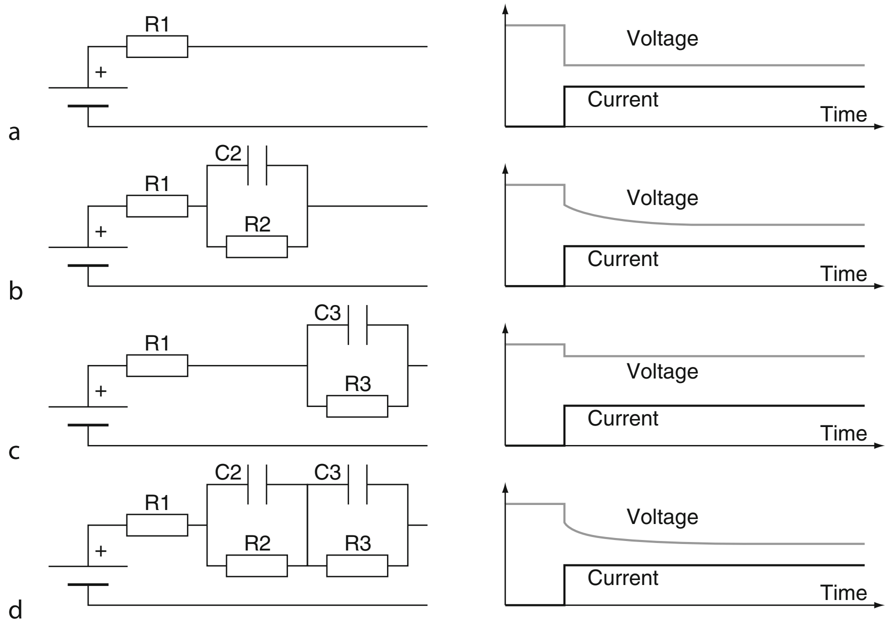
A variation on 2b is 2c, where the time constant $T = R_3 \bullet C_3$ is ~1 ms. This model correctly emulates AC impedances on the order of 1 kHz. This property can however be misleading to the user since such impedances are usually measured with no load by the manufacturer. The user may also misread this impedance as the cell's DC resistance. Figure 2(d) combines 2(b) and 2(c) and thus equally satisfies both the manufacturer and the user.

Internal resistance of a cell results from a series combination of resistances due to bulk metal, chemical processes, and terminals. Varying loads can have dynamic effects on these properties of a battery. Thus the battery's internal resistance (R_i) also has dynamic properties. Davide explains that internal resistance can vary with the following battery characteristics:

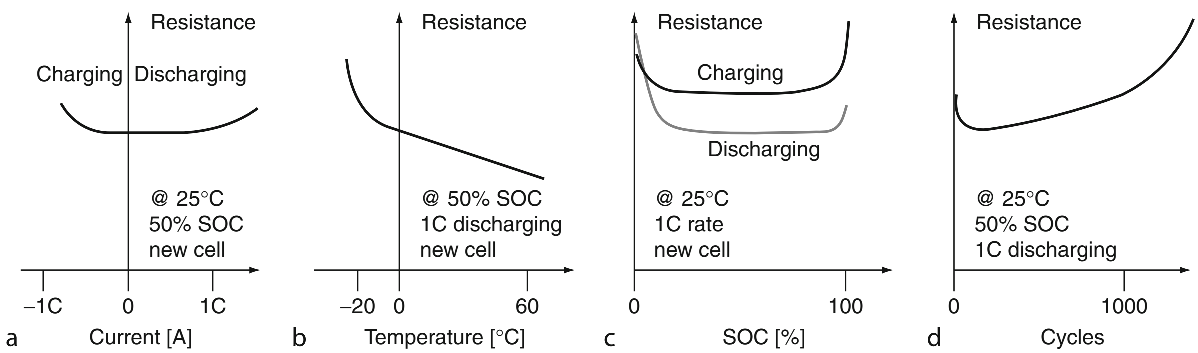
State of charge:	R_i is high for both high and low state of charge levels
Temperature:	R_i is higher at cold temperatures
Current:	R_i is higher at higher currents when charging (compared to the same current when discharging)
Usage:	R_i increases over time with cell usage

Figure 3 shows how the internal resistance of a lithium iron phosphate ($LiFePO_4$) battery varies versus the above four battery characteristics.

For preliminary research purposes, it is entirely possible to create a generic model and vary key



Battery Technologies. Figure 2
Electrical modeling schemes for a battery [5]



Battery Technologies. Figure 3
Internal resistance variation for a $LiFePO_4$ battery [5]

parameters to simulate the performance of various battery chemistries. Table 1 provides a list of key parameters for three batteries chemistry as well as three types of supercapacitors.

Detailed reviews of various battery chemistry compositions are provided in the following sections. We consider not only relevant chemical reactions, but also applications, cost, and efficiency concerns associated with every chemistry type. The following section details lead acid batteries, their cell construction, and the electrochemistry, for several types of lead acid batteries used in EVs and their characteristics.

Lead Acid Batteries

Lead acid (PbA) batteries are inexpensive and have characteristics somewhat suitable for energy storage in EVs. Design is possible for short, high-rate

Battery Technologies. Table 1 Performance parameters

	Lead acid	Nickel metal hydride	Lithium-ion	Super capacitors		
Electrolyte	H_2SO_4 + H_2O	KOH	$LiPF_6$	Aqueous electrolyte	Organic electrolyte	Aqueous electrolyte
Anode	PbO_2	M (Metal)	Graphite	Carbon	Carbon	Metallic
Cathode	Pb	$Ni(OH)_2$	$LiMn_2O_4$	Carbon	Carbon	Metallic
Cell voltage (V)	2.4	1.2	4.0	1	3	1
Specific energy (Wh/kg)	35	50–80	250–400	0.2–1.3	3–6	1
Relaxation time constant (s)	5	2	1	N/A	N/A	N/A
AC impedance time constant (s)	10^{-1}–10^{-3}	10^{-1}–10^{-3}	10^{-3}	N/A	N/A	N/A
Recommended operating temperature (°C)	25	−20 to 50	50	−25 to 85	−40 to 85	−30 to 70

discharges or for bulk energy storage. These batteries are commonly used to power the starter motor of conventional internal combustion engines.

Lead acid batteries are classified into two broad categories, traditional vented lead acid (VLA) batteries and valve-regulated lead acid (VRLA) batteries. The latter have dominated the stationary battery market over the past 20 years [1]. VRLA batteries have immobilized electrolyte and a means to recombine charged gas, thus conserving water in the cell. They are typically smaller than their vented counterparts and require less maintenance. Most of the VLA and VRLA batteries use pasted plate construction, in which a mixture of active materials is pasted onto lead alloy grids. The characteristics of the final battery are heavily influenced by the alloy composition. Tubular plate construction is also quite common, in which the active material is held in non-woven fibrous tubes with a center conductor of lead alloy.

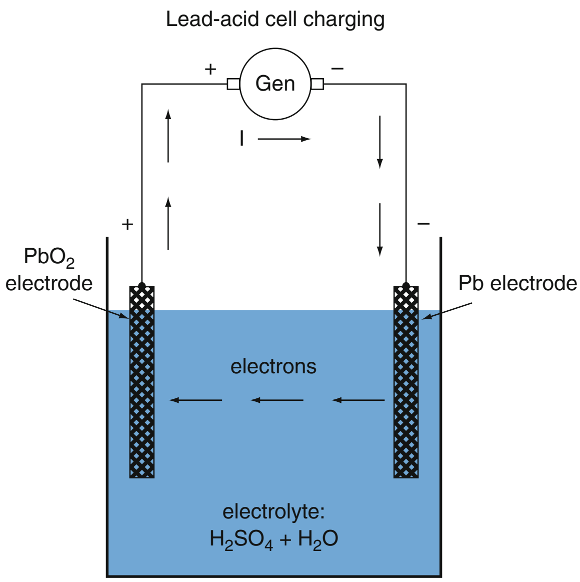
Lead acid batteries have less energy density and specific energy as compared to the more recent lithium-ion and NiMH batteries but these batteries generally have high ampere rating. Since lead acid batteries do not have the deep cycling capability and energy density compared to other batteries used in EVs, they are being replaced by NiMH and Li-ion batteries for traction purposes. However earlier EVs used lead acid batteries like the GM EV1 (Generation 1). The Delphi 704 VRLA-Prismatic battery has an ampere rating of 53 Ah and a specific energy of 35.3 Wh/kg. These batteries have a good cycle life of 15,000–30,000 cycles. In the following section, the cell construction and electrochemistry of lead acid batteries are discussed [4].

Cell Construction and Electrochemistry

All lead acid designs share the same basic chemistry. The positive electrode (cathode) is formed of porous lead dioxide (PbO_2) while the negative electrode (anode) is composed of sponge lead (Pb). Sulfuric acid (H_2SO_4) in water serves as gelled electrolyte between the two electrodes. Lead dioxide at the cathode is supported by a thin lead grid. Figure 4 provides a cross-sectional view of a standard lead acid battery cell.

Pure lead is generally too soft to be used as a plate material and usually requires addition of an alloy. Alloy candidates vary and are responsible for positive plate subtypes such as lead-antimony, lead calcium, and pure lead. Lead-antimony cells are recommended for applications requiring very long life and discharging to depths greater than 20% of rated capacity. Pure lead cells are recommended for float and shallow cycling service where average discharge depth is less than 20%. Finally, pure lead alloy cell types are used when very low charged stand loss is a requirement in the application and occasional deep cycles are expected [6].

During charging, as the cell approaches full charge, a majority of the $PbSO_4$ is converted to Pb and PbO_2. Beyond this point and under high charging voltages, cell voltage becomes greater than the gassing voltage (about 2.39 V per cell) and the overcharge reactions



Battery Technologies. Figure 4
Charging lead acid cell schematic [3]

begin. This results in the electrolysis of the water contained in the electrolyte, and the production of hydrogen and oxygen. In sealed lead acid cells, this reaction is controlled to minimize hydrogen evolution and loss of water by recombining evolved oxygen with the negative plate.

The discharge chemical reactions are as follows:

$$\text{Positive: } PbO_2 + 4H^+ + SO_4{}^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

$$\text{Negative: } Pb + HSO_4{}^- \rightarrow PbSO_4 + H^+ + 2e^-$$

$$\text{Overall: } PbO_2 + Pb + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O$$

As the cell discharges, lead at the anode reacts with hydrogen sulfate ions to form lead sulfate, along with hydrogen ions and electrons. These electrons then travel through the external circuit. Note that sulfuric acid is a strong electrolyte and breaks down into hydrogen and hydrogen sulfate ions even before being placed in the battery. This breakdown is independent of the battery plates. At the cathode, lead dioxide is reduced by the two electrons released at the anode and the lead ion then reacts with sulfate to form lead sulfate along with water. Discharge continues until all of the sulfuric acid is converted to water. Discharging is an exothermic process and charging is an endothermic process.

As discharging progresses, the concentration of the sulfuric acid electrolyte falls. As a result, the no-load (open circuit) voltage of a lead acid cell varies during a cycle from approximately 2.1 V at the top of charge to approximately 2 V at the bottom of discharge. In addition, the decreasing concentration of electrolyte leads to an increasing internal resistance that reduces overall efficiency of the cell. All these factors come together to signify for a given current, the terminal voltage of a lead acid cell is lower at the end of discharge than at the beginning [3].

Lead is insoluble and stays at either plate during charging or discharging. This property allows recharging of the battery. In contrast, non-rechargeable batteries contain reaction products that either convert to an insoluble precipitate or are lost as gas.

Two side reactions can occur in lead acid cells, primarily at the top of charge: hydrogen production from the lead negative plates and oxygen generation from the lead dioxide positive plate. In flooded cells, these side reactions lead to a loss of water that must be made up periodically. The loss of water is particularly high during overcharge and equalization of batteries of cells, which must be performed each full charge and once every 10 or 20 cycles, respectively. Overcharge and equalization both involve charging the lead acid cells somewhat beyond the ampere-hour capacity that has been discharged, so as to ensure that all the electrodes of all the cells of the battery are fully and equally recharged [3].

The next section gives a brief description of the different types of lead acid batteries.

Types of Lead Acid Batteries (by Electrode Material)

Lead Calcium Batteries Lead acid batteries with electrodes that are modified by the addition of calcium are more resistant to corrosion, overcharging, gassing, water usage, and self-discharge. All of these factors shorten the life of a battery. The increased resistance increases the battery life of lead calcium batteries. Additionally, they have a larger electrolyte reserve area above the plates, higher cold cranking ampere ratings, and require little maintenance [4].

Lead-Antimony Batteries Lead acid batteries with electrodes modified by the addition of antimony improve the mechanical strength of electrodes which

is important for EV and deep discharge applications. Water loss and the internal heat are also minimized. They have a longer life than lead calcium batteries. These batteries are also easy to recharge when they are completely discharged and are comparatively less expensive compared to other types of lead acid batteries. However, lead-antimony batteries have a higher self-discharge rate typically 2–10% per week, whereas lead calcium batteries have a self-discharge rate of 1–5% per month [4].

Advanced Lead Acid Batteries In the early part of the decade, the lead acid battery community formed the Advanced Lead–Acid Battery Consortium (ALABC) in a concerted effort to make electric vehicles a reality by overcoming the shortcomings of the VRLA battery. Much has been achieved by the global research and development program of the ALABC [7].

The ALABC originally developed advanced lead acid batteries as a replacement for the more expensive NiMH batteries used in hybrid electric vehicles. These advanced lead acid batteries exhibit better performance as compared to VRLA batteries, in terms of stationary energy storage [8]. Some of the results of research in advanced lead acid batteries are discussed below.

Swelling of the positive active material in the direction normal to the plane of the plate remains a serious concern for VRLA batteries. The tendency for the positive active material to expand with repeated deep cycling is, however, beyond dispute. Experimental work at the University of Brno demonstrated a clear correlation between loss of capacity with cycling and increase of active-material resistance which is presumed to arise as a result of swelling [7].

An in-depth study of positive-grid alloys demonstrated that the introduction of tin brings additional benefits in the form of enhanced corrosion resistance and reduced electronic resistance. Positive grids that contain no antimony but have 1–1.5% by weight of tin do not suffer expansion in the plane of the plate and as a result of the lower corrosion rate, it is possible to contemplate a substantial reduction in grid thickness and weight in order to increase the specific energy [7].

Also, the ALABC development work discovered that adding a small amount of carbon (2–4% by weight) to the negative active material of the electrode minimized negative plate sulfation and enhanced VRLA battery cycling performance in partial-state-of-charge cycling. Battery developers/suppliers who are currently involved in research and development of advanced lead acid batteries include East Penn, North Star, Exide technologies, Axion Power, and Furukawa [8].

Types of Lead Acid Batteries (by Construction)

Flooded/Vented Lead Acid Batteries These batteries have electrodes or plates which are immersed in the electrolyte. The level of the electrolyte reduces as a result of charging and the gases formed which are vented to the atmosphere, so distilled water is added to bring the electrolyte back to its initial level. The most familiar example of a flooded lead acid cell is the 12 V automobile battery.

Valve Regulated Lead Acid (VRLA) Batteries VRLA batteries are also called sealed lead acid (SLA) batteries. They are designed to prevent electrolyte loss through evaporation, spillage, and gassing, which in turn prolongs the life of the battery and reduces maintenance cost. Instead of simple vent caps on the cells to let gas escape, VRLA batteries have pressure valves that open only under extreme conditions. Hydrogen and oxygen are generated by galvanic action of the battery during charging. VRLA batteries need an electrolyte which reduces gassing by impeding the release of these gases to the atmosphere. A catalyst is usually involved that causes the hydrogen and oxygen to recombine into water. This system is called a recombinant system. Since acid electrolyte spillage is eliminated, these batteries are safer [4]. There are two categories of VRLA batteries.

Types of VRLA

AGM (Absorbed Glass Mat) Batteries AGM batteries are similar to VRLA batteries. A boron silicate fiberglass mat acts as a separator between the electrodes and absorbs the free electrolyte. The main purpose of this type of battery is to recombine the hydrogen and oxygen generated during the charging process. The fiberglass mat absorbs and immobilizes the electrolyte, but keeps it in a liquid rather than a gel form. In this way, the electrolyte is more readily available to the plates allowing faster reactions between the

electrolyte and the plate material which gives higher charge/discharge rates as well as deep cycling capability. AGM batteries are very robust and can withstand severe shock and vibrations. Also, the self-discharge rate is low, typically 0.25–0.75% per month. They are also called "starved electrolyte" or "dry" batteries because the fiberglass mat is 95% saturated with the electrolyte and there is no excess liquid [4].

Gel Cell The gel cell is similar to the AGM battery, except that the electrolyte is gelled to immobilize it. The electrolyte is mixed with a silica compound to create the gelled solution. It uses an alternative recombinant technology to promote recombination of the gases produced during charging. It also reduces the possibility of spillage of the electrolyte. Charging rates are limited, because overcharging may cause excess of gases to be released causing damage. The gel cell cannot be fast charged on a conventional automotive charger since it can cause permanent damage [4].

Choosing a Battery

The ideal EV battery should have a constant output voltage at any value of current drawn over the entire state-of-charge (SOC) range and it should also accept high charge rates at the same voltage. No battery has such ideal characteristics but the suitability of a battery for EV use can be determined by the ratio of charging voltage to discharging voltage over the range of SOC and current [9].

Given below are the important factors to consider while choosing a battery for EV use.

Power Battery power performance is generally specified by manufacturers as W/kg at either 2/3 or 1/2 of the open circuit voltage. This ignores the ratio of the terminal voltage under load to that during charge or regenerative braking which is the relevant parameter for EV applications. A more useful figure of merit for comparing the power performance of EV batteries is the power density (W/kg) at 75% end-of-charge voltage (V_{eoc}). For example, if the battery voltage of an EV drops below 75% of V_{eoc} during acceleration, it means that the battery is operating at low cycle efficiency. Another consideration is the cost of the vehicle drive train which is proportional to the product of the maximum voltage rating and the current rating. A low power battery needs more expensive drive train components to achieve a given level of performance because it needs higher current to extract the same power at a lower voltage. A high power battery not only increases vehicle performance but it reduces the cost of the motor and electronics for equivalent performance.

Energy Energy capacity of an EV battery determines the vehicle range. The two parameters which are commonly used to specify energy capacity are specific energy and energy density. Reducing energy consumption is often a better way to increase EV range than increasing battery capacity. EV batteries cannot yet match the energy density of gasoline but provide power to exceed the acceleration of conventional vehicles. One of the unique features of EVs is the capability to provide high peak power and excellent acceleration without sacrificing operating efficiency [9]. The Tesla Roadster sports car demonstrates this by operating at 180 Wh/mile in normal driving and offering acceleration from 0 to 60 mph in 3.7 s, which is quicker than a gasoline-powered Mercedes-Benz SLR McLaren. The first-generation EV1 used Delphi's valve-regulated lead acid batteries, which is capable of operating at 164 Wh/mile. Nickel metal hydride batteries (NiMH) batteries (See section "Nickel-Cadmium Battery") have twice the energy density and specific energy compared to lead acid batteries. An EV fitted with a NiMH battery which is of the same size and weight as a lead acid battery has twice the range. However, due to power considerations, it is not necessary that an EV could be built to match the range of a lead acid battery powered EV using a NiMH battery with half the size and weight [9].

Cost Although lead acid batteries have less energy density and specific energy and are bulkier compared to NiMH and lithium-ion batteries, they are typically inexpensive. Today, a lead acid battery pack for an EV costs \$215/kWh, a NiMH battery costs \$350/kWh, and a lithium-ion battery costs \$400/kWh [9]. The lower cost of the lead acid battery makes it an affordable technology and also decreases the overall cost of EVs. Axion Power, a firm based in Pittsburgh, Pennsylvania, has come up with a new

technology called lead-carbon battery which is derived from traditional lead acid battery technology. Axion Power has managed to convert a pickup truck to run on a pack of the lead-carbon battery for around $8,000 [10]. If further cost reductions are achieved in the production of batteries, then EV pricing can become competitive with conventional vehicles.

Temperature Effects on Batteries Batteries function because of electrochemical reactions (charging and discharging) taking place in the cell. These chemical reactions are dependent on temperature. Nominal battery performance is usually specified for working temperatures between 20°C and 30°C. However the actual performance can deviate substantially if the battery is operated at higher or lower temperatures. The operation of any battery generates heat due to the I^2R losses as current flows through the internal resistance of the battery whether it is being charged or discharged. This is also known as electrical heating or Joule heating. During discharge, since the total energy within the system is fixed, the temperature rise is limited by the available energy. Another factor which affects the performance of a battery is the ambient temperature. If the ambient temperature is higher than the temperature of the battery, the battery gains heat from the surrounding and if the ambient temperature is lower, the battery losses heat to the surrounding. The difference in the ambient and the optimal operating temperature of a battery reduces its performance. Overheating may also be caused in batteries because of highly exothermic reactions, which generate a lot of heat and may ultimately damage the batteries [4].

Lead acid batteries are exothermic during charging, which makes their temperature rise dramatically. If the temperature exceeds beyond a limit, the battery may be damaged. Also, being a galvanic cell, its internal resistance is temperature dependent. Internal temperature decreases as the temperature rises due to the increase in electron mobility. The cell is very inefficient at low temperatures but the efficiency improves at higher temperatures due to the lower internal impedance and also because of the increased rate of chemical reactions. However, the lower internal resistance also causes the self-discharge rate to increase. Additionally, the cycle life deteriorates at high temperatures. Some form of heating and cooling is therefore required to maintain the battery within a specific temperature range to achieve optimum performance [4].

Life Battery life represents an important parameter in battery performance that affects customer satisfaction and overall cost. Battery life depends mainly on the number of cycles. Technical factors such as temperature control, charging procedures, and exposure to abusive conditions also play an important role in determining the battery life. Lead acid batteries in EVs may last 15,000–30,000 cycles if used regularly. However, they start deteriorating after 2 years regardless of the kind of use. Lead acid batteries respond well to battery management systems that control temperature and maintain SOC equalization. A factor related to battery life is the battery residual value. Although virtually all EV batteries are recycled for economic and environmental reasons, EV batteries may retain value greater than their salvage value after their useful life as a traction battery is complete. AC Propulsion regularly sells spent traction modules as starter batteries with a 2-year warranty for $25 or about $50/kWh. These modules are retired because their capacity is diminished by 30% or more, but they serve well as starter batteries [9].

Table 2 below shows some typical specifications of VRLA batteries used in EVs.

Battery Technologies. Table 2 Specifications of VRLA batteries in EVs [11, 12]

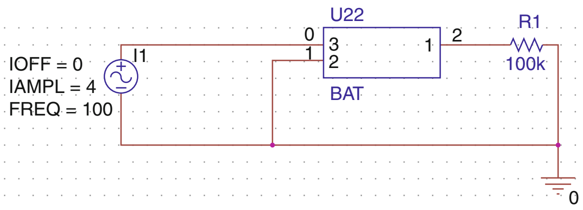
Electric vehicle	1998 Ford Ranger EV	GM EV 1, first model
Manufacturer	Delphi	Delphi
Number of modules	39	26
Weight of module (kg)	19.3	18.8
Nominal module voltage (V)	8	12
Nominal system voltage (V)	312	312
Nominal capacity (Ah)	60 (100% capacity)	53 (50% capacity)
Specific energy (Wh/kg)	23.7–25.2	26.3–31.9
Efficiency (Wh/mile)	237–356	115–164

Lead Acid Battery Circuit Model

Consider Fig. 5 as a lead acid cell model. We construct this circuit using PSpice software. Consider the cell to provide 2 V nominal voltage, 10 Wh capacity, round-trip efficiency of 90%, and 70% initial state of charge. Here, available energy during operation is computed as

$$\mathrm{SOC}(t) = \mathrm{SOC}_{\mathrm{initial}} + \frac{1}{\mathrm{Capacity(Wh)}} \int \frac{kV_1 I_{\mathrm{bat}}}{3600}\,dt$$

where k is cell efficiency, V_1 is cell voltage, and I_{bat} is cell current. During discharge, current flows in the opposite direction when compared to charging, leading to a minus sign before the integral. Division by 3,600 is needed to ensure that cell capacity is in units of watt-hours, Wh. Alternate charging and discharging operation is conducted by applying AC current I_{AC} at 4 A, 100 Hz, as shown in Fig. 16. Resistor R_1 is chosen arbitrarily high to ensure there is no voltage drop at the cell's output terminals.



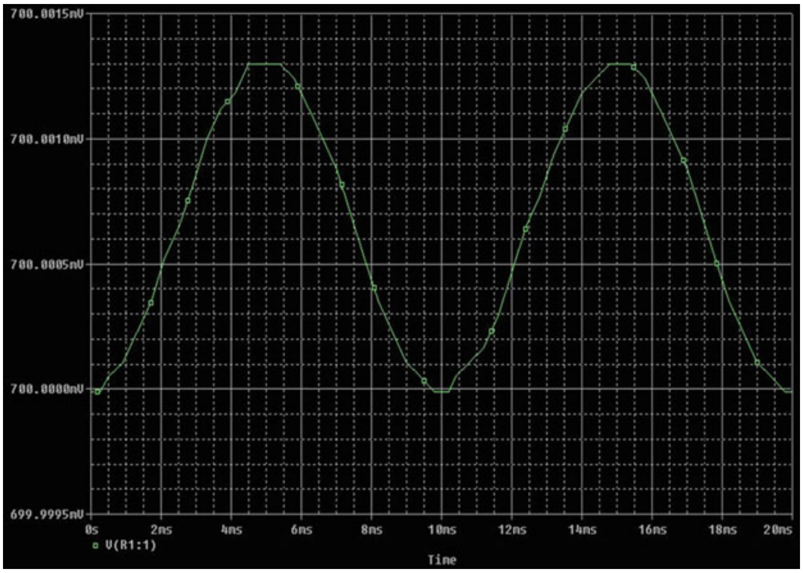
Battery Technologies. Figure 5
Lead acid cell model using PSpice

Figure 6 shows the state of charge (SOC) of the cell.

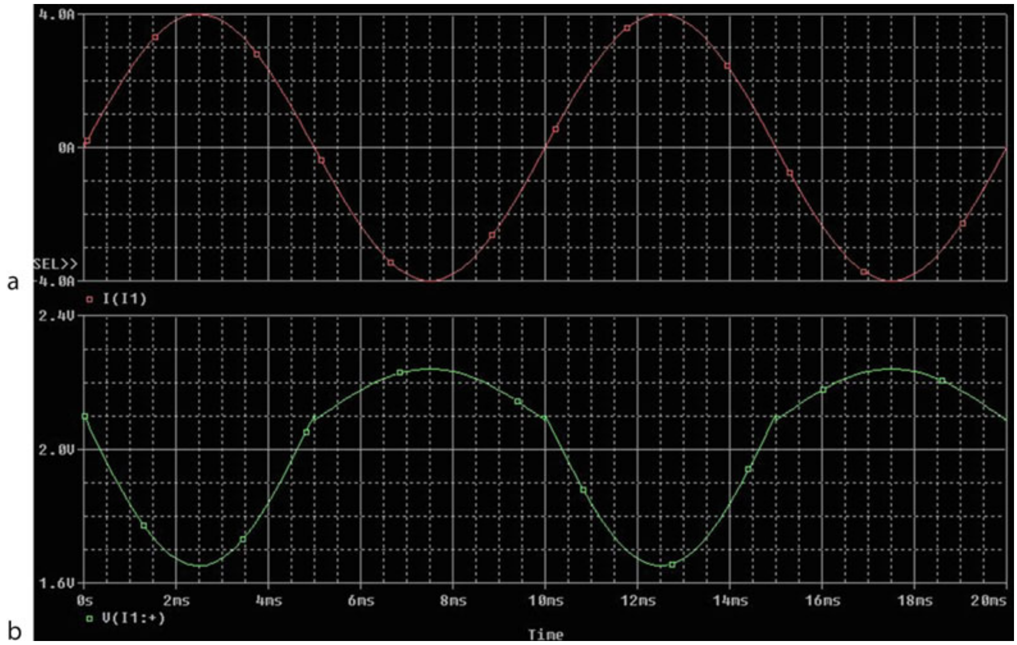
Note that the Y-axis provides state of charge as a percentage. Figure 7b provides cell voltage V_1, whereas I_{AC} is shown in 7a.

Note that in addition to the nominal 2 V, cell voltage is a function of state of charge of the cell. For example, a certain degree of overvoltage can occur with high state of charge. A 70% state of charge leads to a cell (over) voltage of 2.1 V in 7b.

When I_{AC} is positive, current travels into the cell, simulating charging. This is evident in Fig 18b where V_1 drops while I_{AC} increases in the positive direction. Negative I_{AC} implies cell discharge, with V_1 above the nominal 2 V. An immediate advantage of lithium-ion batteries is their diversity in operation. Figure 19 shows only a few possible chemical combinations.



Battery Technologies. Figure 6
Cell state of charge



Battery Technologies. Figure 7
Applied AC current and cell voltage

Nickel-Cadmium Battery

The nickel-cadmium battery commonly abbreviated as NiCd battery is a type of rechargeable battery which works by oxidizing nickelic hydroxide ($Ni(OH)_2$) into nickelous hydroxide (NiOOH) and has metallic cadmium as electrodes. The charge/discharge reaction can be given as follows:

$$2Ni(OH)_2 + Cd(OH)_2 \rightleftarrows 2NiOOH + Cd + H_2O$$

The features of this battery are that the electrolyte does not take part in any of the chemical reactions and the active materials are insoluble in the electrolyte. Nickel-cadmium batteries have a reputation for their robustness, reliability, and service life. They can also operate under severe weather conditions, with operating temperatures ranging from $-40°C$ to $+60°C$ (because the electrolyte has a very low freezing point), excellent cycling capability (up to 2,000 cycles at 80% depth of discharge), long storage life, and low or zero maintenance [10, 11].

NiCd batteries have been used extensively in consumer electronics and power tools. In the recent past, NiCd batteries have also been used in electric vehicles, an example being the Peugeot 106 electric, which used NiCd batteries manufactured by SAFT [12].

Nickel-cadmium cells have a nominal cell potential of 1.2 V. This is lower than the 1.5 V of many popular primary cells, and consequently they are not appropriate as a replacement in all applications. NiCd batteries have an energy density of 40–60 Wh/kg, which is greater than that of lead acid batteries, but less when compared to NiMH and Li-ion batteries [14].

Advances in battery-manufacturing technologies throughout the second half of the twentieth century have made batteries increasingly cheaper to produce; about 1.5 billion NiCd batteries were produced annually up until 2000. NiCd batteries never became widely used as a replacement for lead acid batteries in the areas where those batteries dominate, mainly because of the toxic nature of the battery and the reduction in its capacity as the battery ages. However, NiCd batteries had an overwhelming majority of the market share for rechargeable batteries in consumer electronics up until the mid-1990s [10].

Nickel Metal Hydride Batteries

Nickel metal hydride (NiMH) batteries were first developed in the late 1980s and ever since have been used in portable electronic devices like camcorders, power tools, and cell phones. NiMH batteries have high storage capacity and relatively high ramp rates. They have succeeded lead acid batteries owing to higher number of cycles and higher energy density [14]. A study by EPRI in 2004 showed that NiMH batteries are acceptable for full-function EVs, city EVs, and plug-in hybrid electric vehicles (PHEVs) [8].

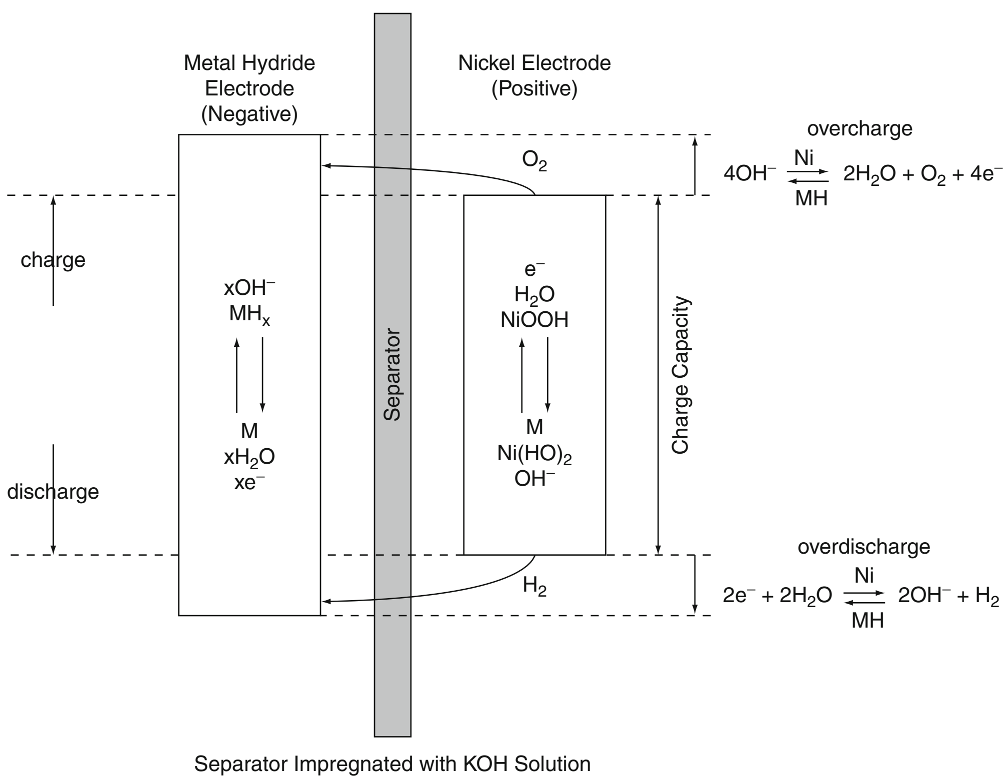
Although the technology was largely driven by military and government research in its earlier days, recently, significant contributions have been made by EV manufacturers. Applications of NiMH EV batteries include all PHEVs manufactured by General Motors, Honda, Ford, Toyota, and the Vectrix scooter, among others. The town of Nice, France, now operates its low floor tram, manufactured by Alstom using NiMH batteries. Honda's humanoid prototype robot ASIMO is another application.

Nickel Metal Hydride Cell Construction and Chemistry

The basic representation of a NiMH cell is shown in Fig. 8. The positive electrode of a NiMH cell consists of a spongy mass of nickel hydroxide $Ni(OH)_2$. During charge, the positive electrode releases hydrogen into the electrolyte, which in turn combines with hydroxide (OH^-) ions. This reaction results in nickel oxyhydroxide (NiOOH) on the positive electrode and water (H_2O) in the electrolyte plus one free electron, e^-.

The equation for the positive electrode can be given by:

$$Ni(OH)_2 + OH^- \underset{\text{discharge}}{\overset{\text{Charge}}{\rightleftarrows}} NiOOH + H_2O + e^- \tag{1}$$



Battery Technologies. Figure 8
Schematic representation of a NiMH cell [7]

The negative electrode contains a metal alloy–hydride complex. In an exothermic reaction, the water (H_2O) from the electrolyte combines with the free electron to form metal hydride (MH) and hydroxide (OH^-). The metal alloy absorbs and desorbs the hydrogen, allowing the electrochemical reaction to occur without producing hydrogen gas. Equation 2 shows the net chemical reaction that occurs at the negative electrode during charge and discharge.

$$M + H_2O + e^- \underset{\text{discharge}}{\overset{\text{Charge}}{\rightleftarrows}} MH + OH^- \qquad (2)$$

The most commonly used electrolyte is a solution of aqueous potassium hydroxide, KOH, in which the KOH concentration ranges from 25% to 40% by mass. The two equations show that there is no net change in electrolytic quantity. This result contrasts with other electrolyte systems like NiCd, where water is generated at both electrodes during charge and consumed at both electrodes during discharge. Although transient electrolyte concentration gradient occurs in NiMH batteries, its constant average concentration has good overall performance in gas recombination, kinetics, high and low temperature operation, and resistance to cycle life limitations caused by corrosion and swelling [7].

Overcharge and Over-discharge Reactions

The NiMH battery has overcharge and over-discharge reactions that allow the battery to handle abuse conditions of overcharge and over-discharge without adverse effects. The reaction that takes place at the two electrodes during overcharge is an oxygen recombination reaction. It can be shown as follows:

At the positive (Ni) electrode OH^- ions are oxidized generating oxygen:

$$4OH^- \leftrightarrow 2H_2O + O_2 + 4e^-$$

At the negative (MH) electrode the oxygen is reduced:

$$2H_2O + O_2 + 4e^- \leftrightarrow 4OH^-$$

The net result is generation of heat which is proportional to the energy input. This occurs at the expense of increasing the stored charge in the battery. If the rate of charge input exceeds the rate of recombination, the cell pressure increases, which may lead to cell damage.

During over-discharge, hydrogen is released at the positive electrode and recombined at the negative electrode. The reactions are as follows:

At the positive electrode, water is reduced and hydrogen gas is released:

$$2H_2O + 2e^- \leftrightarrow H_2 + 2OH^-$$

The hydrogen gas is then oxidized at the negative (MH) electrode:

$$H_2 + 2OH^- \leftrightarrow 2H_2O + 2e^-$$

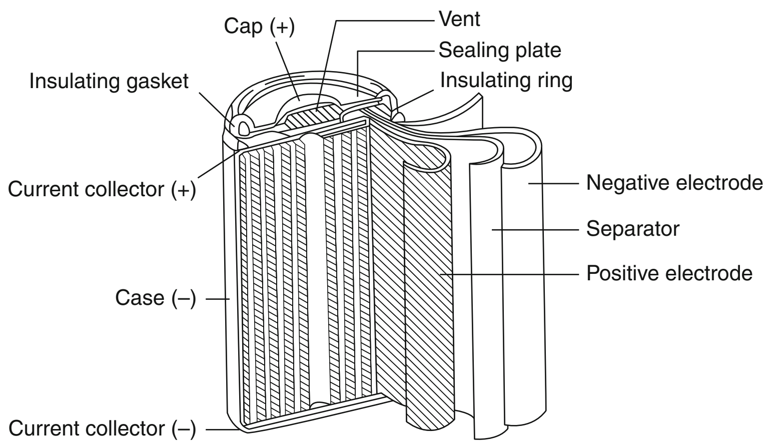
The ability of the NiMH cell to tolerate over-discharge is very important for large series strings of batteries since capacity mismatches may cause some cells to over-discharge. To ensure that the overcharge and over-discharge reactions function properly and thus control the buildup of cell pressure, the NiMH battery is constructed with the Ni electrode as the capacity limiting electrode and the MH electrode with excess capacity to allow recombination reactions to take place during overcharge and over-discharge [7].

Types of NiMH Batteries

The earliest pioneering work on NiMH batteries was performed at the Battelle-Geneva Research Center starting after its invention in 1967. These batteries showed high specific energy up to 50 Wh/kg, power density up to 1,000 W/kg, and a reasonable deep cycle life of 500 cycles (depth of discharge: 100%). Due to the inherent deep cycling capability and the high specific energy, NiMH batteries have been used in EVs. The two major types of NiMH batteries used today are the cylindrical batteries and the prismatic batteries. The next section describes the cylindrical NiMH batteries in detail giving the battery structure and the battery characteristics. The later section describes prismatic NiMH batteries and gives the comparison between the two of them. Currently, there are over two million HEVs running worldwide, which use NiMH batteries [15].

Cylindrical NiMH Cell

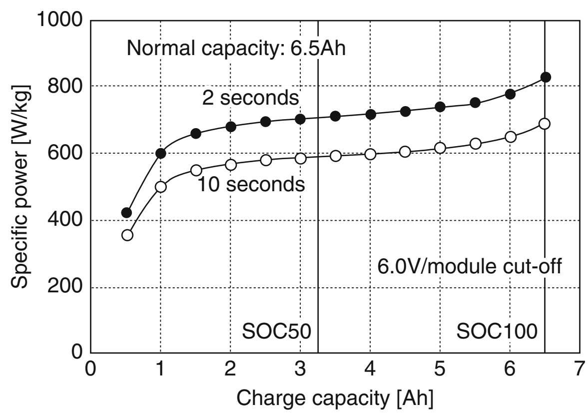
Battery Structure The single cell shown in Fig. 9 is a sealed cylindrical battery of D-size with a diameter of 32 mm and a height of 60 mm. A sealing plate is equipped with a valve to prevent bursting with an



Battery Technologies. Figure 9
Structure of a cylindrical battery

Battery Technologies. Table 3 Characteristics of a single cylindrical cell and battery consisting of six cells [13]

	Single cell	Battery module (six cells)
Output power	625 W/kg, 2,160 W/l	600 W/kg, 2,070 W/l
Input power	500 W/kg, 1,720 W/l	480 W/kg, 1,660 W/l
Energy density	45 Wh/kg, 172 Wh/l	43 Wh/kg, 161 Wh/l
Nominal voltage	1.2 V	7.2 V

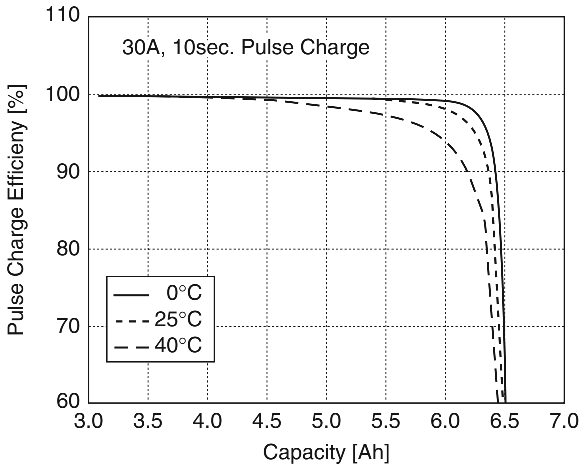


Battery Technologies. Figure 10
Specific power of a cylindrical battery at different state of charge levels [13]

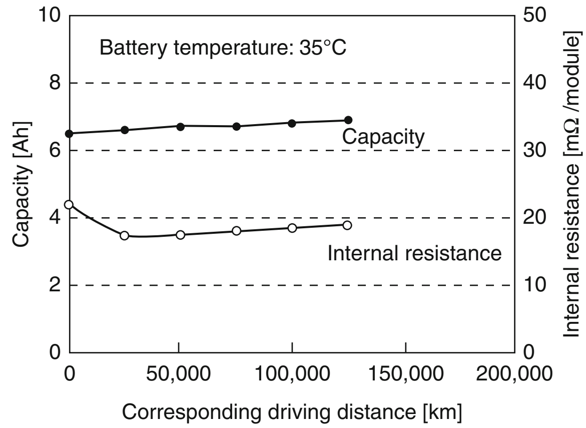
increase in internal pressure. The battery case is made of steel and both positive and negative electrodes are coiled and separated by a separator. This battery optimizes the reaction area of the electrodes, reducing resistance for current collection and improving electrolyte composition to obtain high power characteristics. The nominal battery capacity is 6.5 Ah and the maximum output power is more than 100 W per cell. To reduce the internal resistance and shield against vibrations, disk plates are inserted for cell connection [13].

Battery Characteristics Table 3 gives the characteristics of a single cylindrical cell and battery consisting of six cells.

Discharge Power Characteristics Figure 10 shows the specific power characteristics of a battery module that consists of six cells at different state of charge (SOC). The module provides 800 W in 2 s and 650 W in 10 s. As seen in the graph, for a given range of charge capacity, the specific power is almost constant. Also, for the 50% SOC and 100% SOC, there is not much variation in specific power, giving 650 W/kg in 2 s and 600 W/kg for a 10 s duration. Relatively constant input and output power is highly desired by EV manufacturers. It can be clearly seen from the graph that NiMH prismatic batteries deliver an almost constant power for any SOC, which is highly desirable in batteries for EVs.



Battery Technologies. Figure 11
Pulse charge efficiency of cylindrical battery module at different temperatures [13]



Battery Technologies. Figure 12
Life cycle characteristics of cylindrical battery module with simulated actual driving pattern [13]

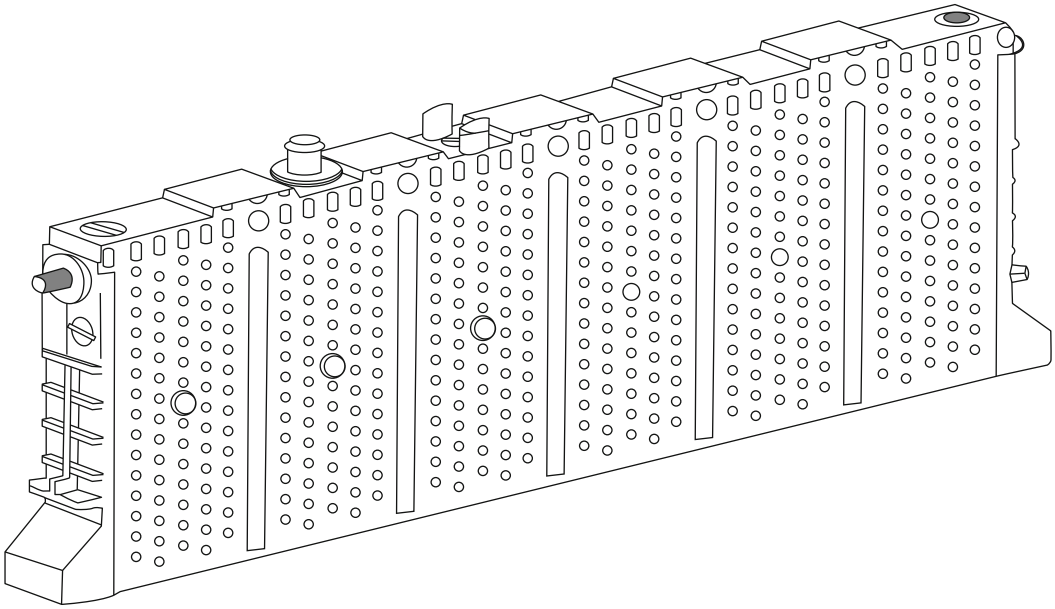
Charge Efficiency For practical use, high charge efficiency is required over a wide temperature range. Figure 11 shows the battery has a very high charge efficiency, which provides high regenerative acceptability over the SOC range, mostly used during normal vehicle operation. The ampere-hour charge efficiency is nearly 100%. Also because of the very small energy loss, heat generation of the battery is minimized.

Life Cycle Characteristics To preserve an active battery system, flow of power in and out of the battery needs to be maintained, even if minimal. The battery's controller needs to ensure that the battery is neither fully charged nor completely discharged. To test such operating conditions, a life test was conducted at Panasonic's test facility in Shizuoka, Japan. One example of the results is shown in Fig. 12 [13]. The test provides results in which the input and output power simulate real vehicle driving at 35°C. As a result, the durability was found to be equivalent to more than 100,000 km driving without deterioration of battery characteristics.

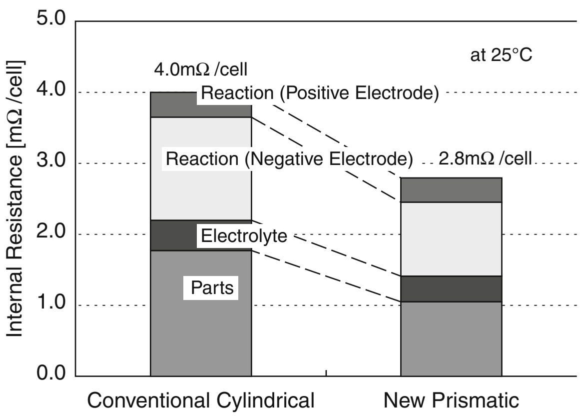
Prismatic NiMH Battery

Structure To improve power, reduce the number of connected parts. Figure 13 shows the appearance of a prismatic module design consisting of six cells in series. The conventional cylindrical module has connecting plates to connect cells and plastic insulating rings to prevent external short circuits. The prismatic module adopts internal connection; therefore, connecting plates and plastic insulating rings are not required. As a result, a shorter current path is accomplished. The investigation of electrode dimensions and current collector design shows that the current flow path is shortened. By thinning the positive and negative electrodes, the number of electrodes are increased, which increases the reaction area and decreases the current density. Resin material is used to make the battery case, which provides increased safety and reliability. The resin material makes it easy to design bumps and ribs on the side of the battery case. The bumps and ribs provide cooling and also reduce the pack volume by 40%. The resin also reduces 20% of the prismatic battery's weight compared to a cylindrical battery pack. The six cells are internally connected to form one module. External connection parts like bus bars and connecting plates are also not required [13].

Figure 14 shows the improved power characteristics and reduced internal resistance of this battery, as compared to the cylindrical battery. The main source of the reduction in internal resistance is the components. A high specific power of 1,000 W/kg, which is higher than that of the conventional cylindrical battery, is also achieved.



Battery Technologies. Figure 13
Prismatic NiMH battery [13]



Battery Technologies. Figure 14
Internal resistance of prismatic and cylindrical battery cell before activation [13]

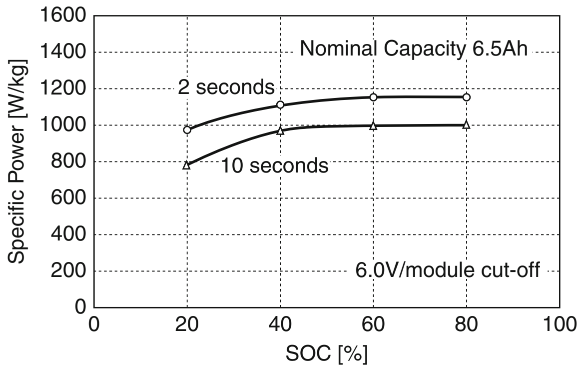
Battery Technologies. Table 4 Comparison between prismatic and cylindrical battery modules [13]

	Prismatic module	Cylindrical module
Dimensions (mm)	19.6 × 106 × 275 (width × height × length)	35 × 384 (diameter × length)
Nominal voltage (V)	7.2	7.2
Nominal capacity (Ah)	6.5	6.5
Specific power (W/kg)	1,000	600
Specific energy (Wh/kg)	46	43
Weight (g)	1,020	1,090

Table 4 shows the module characteristics of both prismatic and cylindrical battery types. It is clear that the prismatic design is superior to the cylindrical design.

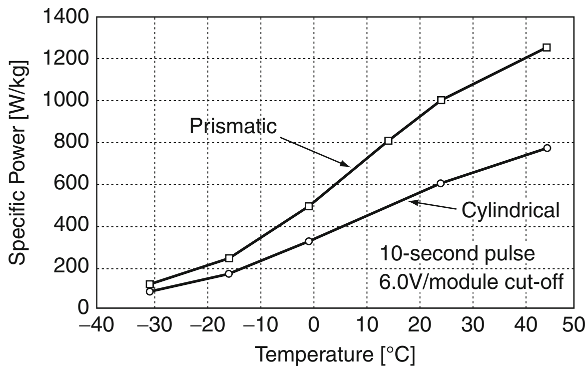
Discharge Power Characteristics Figure 15 shows the power characteristics of the prismatic module at different SOC. This battery provides 1,000 W of power per kilogram for 10 s and 1,150 W of power for 2 s with the SOC maintained in a range 40–60%. It also has high power density at low SOC; about 800 W/kg for 10 s and 1,000 W/kg for 2 s at 20% SOC.

Figure 16 shows the power characteristics at different temperatures for the cylindrical battery and the prismatic battery. As seen, the characteristics of



Battery Technologies. Figure 15

Specific power of prismatic battery at different SOC [13]



Battery Technologies. Figure 16

Specific power of prismatic and cylindrical battery module at different temperatures [13]

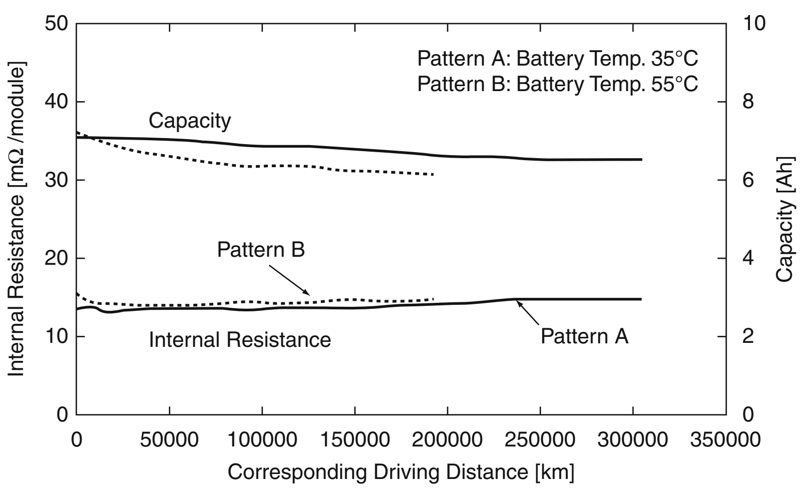
the prismatic battery are better (490 W/kg at 0°C and 120 W/kg at −30°C). Also the temperature where power discharge of 200 W/kg is possible is reduced by about 10°C as compared to the cylindrical battery.

Life Characteristics of Prismatic Batteries In Fig. 17, Pattern A represents a normal driving profile, with a maximum SOC deviation of 15% and pattern B represents a high load driving profile with a maximum SOC deviation of 30%. After tests corresponding to a driving distance of 300,000 km with pattern A at 35°C, there was no deterioration observed in battery performance. Also, with pattern B at 55°C, the battery was able to achieve a driving distance of 200,000 km [13].

Figure 18, above, shows the EV-95 (95 Ah) and EV-28 (28 Ah) units developed by Panasonic for EVs. EV-95 has long life characteristics of more than 1,000 cycles and 4 years of onboard driving [13].

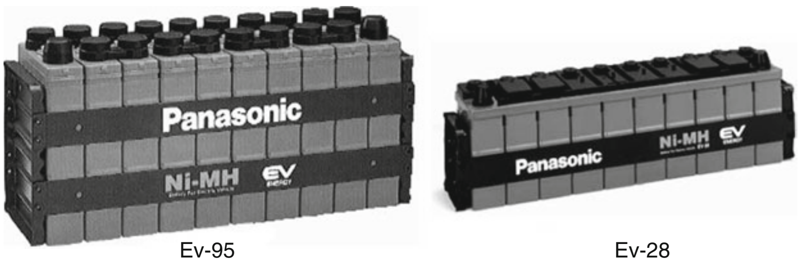
The batteries shown above have the following characteristics:

1. Optimization of additives (Y_2O_3) for excellent charge efficiency of the positive electrodes
2. $MnNi_5$ system of hydrogen-absorbing alloy for the negative electrodes
3. High performance, hydrophilic-treated polypropylene separator



Battery Technologies. Figure 17

Life cycle characteristics of prismatic batteries [13]



Battery Technologies. Figure 18
EV-95 and EV-28 batteries by Panasonic

Battery Technologies. Table 5 Basic characteristics of the EV-28 and EV-95 batteries [13]

	EV-28	EV-95
Dimensions (width × height × length) mm × mm × mm	75 × 110 × 388	116 × 175 × 388
Nominal voltage (V)	12	12
Nominal capacity (Ah)	28	95
Weight (kg)	6	18.7
Specific energy (Wh/kg)	58	65
Specific power at 80% depth of discharge (W/kg)	300	200
Self discharge at 45°C, 1 month (%)	20	20
Cycle life at 25°C ambient temperature, 80% DOD (cycles)	>1,000	>1,000

The electrode groups consist of alternately stacked positive electrodes and negative electrodes interleaved with separators. Inserting these electrode groups into a resin battery case and sealing with a cover equipped with a valve after filling with alkaline electrolyte forms the cell. A battery module consists of ten cells connected in series by metal plates and these are configured to permit airflow between the cells to ensure a uniform temperature distribution.

Table 5 gives the characteristics of the EV-28 and EV-95 batteries manufactured by Panasonic.

Below is Table 6, which gives characteristics of NiMH batteries, produced by Texaco Ovonic Battery Systems and VARTA.

Battery Technologies. Table 6 Battery characteristics [8]

Manufacturer	Battery design	Cell size (Ah)	Specific energy (Wh/kg)	Specific power (W/kg)
Texaco Ovonic battery	High power	7.5	~40	650
	Medium power	28	48	~440
	Medium power	45	71	~390
VARTA	High power	10	30	630
	Medium power	45	50	220

The second-generation GM EV1 used NiMH batteries. Table 7 shows the specifications of that battery.

Lithium-Ion Batteries

Lithium-Ion Battery Chemistry

Lithium is the least dense of all solid metals, has the greatest electrochemical potential, and provides the largest energy density by weight. For many years, lead acid had been the predominant battery for large-scale equipment. G. N. Lewis pioneered early work with lithium-ion battery technology but it was not until the early 1970s before it became commercially viable. Because of the inherent instability of lithium metal, early attempts at rechargeable batteries failed. Research then shifted to lithium-ion-based composites which, although less dense, are safer to use. Lithium-ion

Battery Technologies. Table 7 GM EV 1 (generation 2) battery specification [16]

Manufacturer	Ovonic energy products
Type	Nickel metal hydride
Number of modules	26
Weight of module	18.3 kg
Weight of pack(s)	481 kg
Nominal module voltage	13.2 V
Nominal system voltage	343 V
Nominal capacity (50% charge capacity)	85 Ah

Battery Technologies. Table 8 Redox potential [7]

Electrode reaction	Potential (V)	Electrode reaction	Potential (V)
$Li^+ + e \leftrightarrow Li$	−3.01	$Cu^{2+} + 2e \leftrightarrow Cu$	0.34
$Na^+ + e \leftrightarrow Na$	−2.71	$Ag^+ + e \leftrightarrow Ag$	0.80
$Ni^{2+} + 2e \leftrightarrow Ni$	−0.23	$Cl_2 + 2e \leftrightarrow 2Cl^-$	1.36
$Pb^{2+} + 2e \leftrightarrow Pb$	−0.13	$F_2 + 2e \leftrightarrow 2F^-$	2.87

batteries emerged during the early 1990s. Today, lithium-ion is the fastest growing and most promising battery chemistry.

As mentioned earlier in section "Basic Characteristics of Batteries," a battery functions as a combination of chemical reactions, oxidation at the anode (where electrons are generated in discharge mode), and reduction at the cathode (at which electrons enter the cell). Depending on the direction of the current (charge or discharge) each electrode is either the cathode or the anode. The electrolyte can serve as a reaction propellant or even as an integral part of the reaction. This combination of reactions is referred to as *redox*. Table 8 provides redox reaction potentials for eight elements.

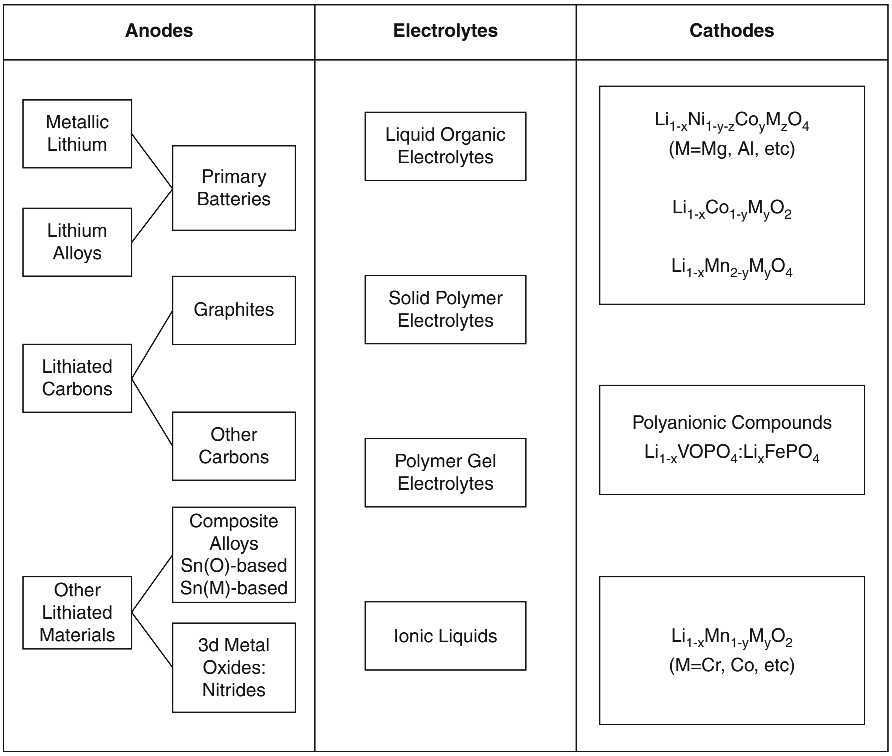
Lithium and fluoride generate the highest potential during oxidation and reduction, respectively [7]. A significant advantage of lithium-ion batteries is their efficiency in charge retention and energy supply. The internal resistance of lithium-ion cells is comparatively low, which means they do not lose a considerable amount of energy as heat (I^2R loss) [8]. In general, the internal resistance of a cell is modeled as a resistor in series with an ideal voltage source. Maximum efficiency occurs with a low internal series resistance and a large load resistance. Maximum power can be extracted from a cell when load resistance is equal to the cell's internal resistance. Under this condition half the total power is expended as heat, while the other half is available for use. The availability of high power output is a useful property for lithium-ion cells, especially when instantaneous power is required. Consider the example of a race car looking to set a new quarter-mile speed record. This car would need high instantaneous power without regard to cell degradation due to overheating.

Operation

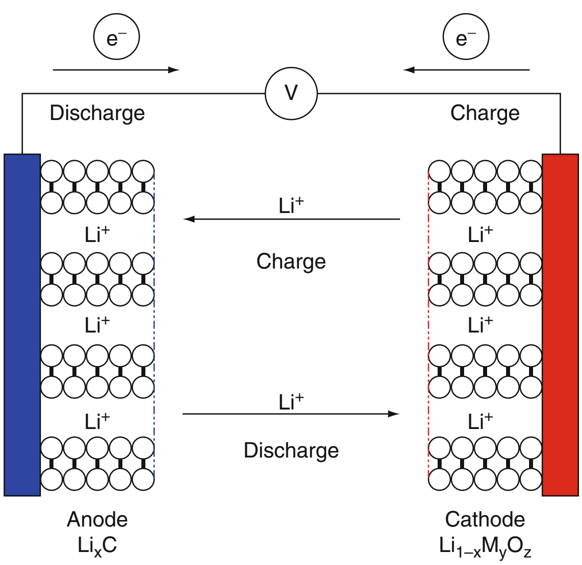
Numerous lithium-based alloys are available for use as anode. Lithium polymers are considered commercially safe, while metallic lithium is still at the developmental stage [17]. Charge flow for any of the combinations in Fig. 19 is typically the same, as shown in Fig. 20.

A common electrolyte is lithium hexafluorophosphate ($LiPF_6$). It was chosen for its high redox potential. Ehsani et al. [17] mentions that $LiPF_6$ is unstable under high heat and moisture. Hydrofluoric acid (HF) is produced as a by-product to the electrolyte's reaction with water. For this reason, there was significant opposition to its use in the early 1990s. Since then however, it has been revealed that a small amount of HF increases life cycle, because of the formation of a strong passive layer on the cathode.

The addition of HF prevents formation of lithium dendrite. (Most metals are combined with alloys for dexterity and strength. Due to the presence of alloys, the metal tends to exist in a nonuniform, snowflake-like distribution called *dendrite*.) $LiPF_6$ is also easily soluble in the solvent, making it a good solid interface on the surface of anode materials. Lithium-ion is considered to be the current generation technology for EV batteries, in part because of it high energy density. Also, lithium has the highest redox reaction potential of any metal. It is also necessary to consider the fact that key elements of lithium-ion batteries are facing exhaustion.



Battery Technologies. Figure 19
Numerous chemical combinations for lithium-ion batteries

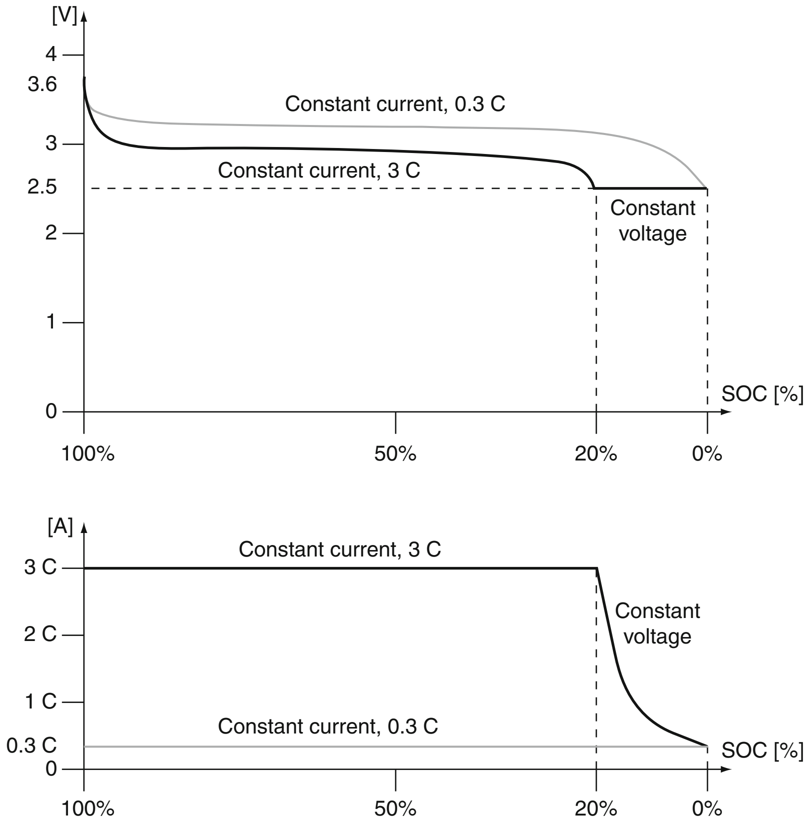


Battery Technologies. Figure 20
Charge flow for lithium-ion batteries [17]

Cobalt metal, used for cathode, has been in shortage for quite some time [17]. Most metals are combined with alloys for dexterity and strength. Due to the presence of alloys, the metal tends to exist in a, nonuniform, snowflake-like distribution called dendrite [17].

Efficiency

Lithium-ion batteries are practically 100% charge efficient, according to Brodd et al. [5]. In essence, all the charge lost during discharging is recovered during charging. Note that there is a net loss in energy during each complete charging/discharging cycle. This is because the cell voltage is lower during discharging as compared to the charging cycle. Figure 21 provides discharge curves for voltage and current of a lithium-ion cell. Note that the voltage continues to drop during discharge before stagnating at a constant level toward the end of charge availability. This constant voltage



Battery Technologies. Figure 21
Voltage and current during discharge [18]

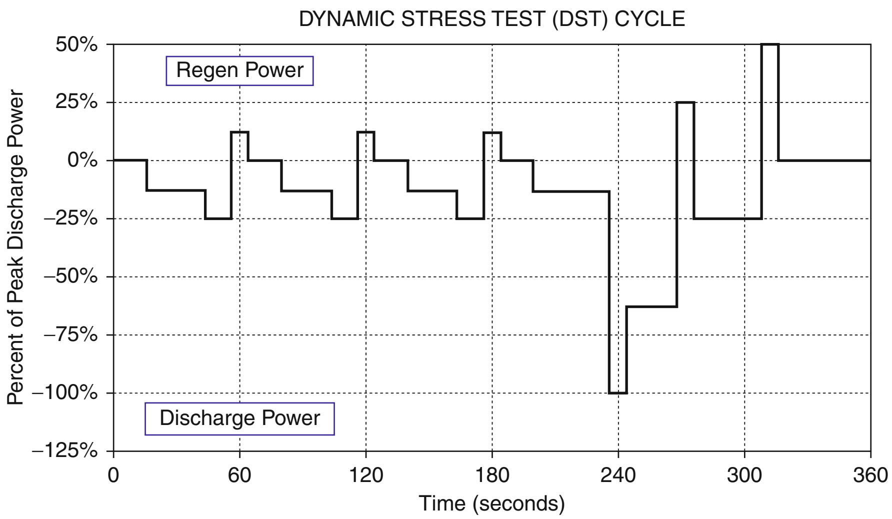
can be attained by discharging at a lower current, as shown in the current curve of Fig. 21. As the current drops to zero, the total charge from the cell adds up to the same value regardless of the rate of discharge (whether the discharge was at a low current or at a high current) [5].

Applications that require constant current will be unable to extract the last bit of energy out the battery. Other applications, such as for EVs, have more flexibility. Some of today's EVs can operate at lower torque, which implies lower current, to allow the driver to reach a safe location before running out of battery power. Such applications can use the entire charge contained in a battery.

Although not obvious, both the graphs in Fig. 21 are related. As a cell ages, it appears to gradually lose capacity. Davide [18] explains that this capacity is actually unused, but not lost. Internal resistance of a cell increases with age, therefore the cell gets undercharged and under-discharged along the process. This issue can be resolved by allowed fixed cutoff voltages to vary internally. Due to fixed cutoff voltages, the cell charges/discharges less and less each time due to increasing internal resistance, resulting in an apparent loss of capacity. By raising the upper cutoff voltage during charge and lowering the lower cutoff voltage during discharge, we can recover some of this lost capacity. A battery management system that is able to measure a cell's internal resistance and compensate its cutoff voltage accordingly can make better use of the cell's capacity [18].

Reliability

To minimize operation and maintenance (O&M) costs for the customer, it is essential for a battery manufacturer to conduct rigorous stress tests on their battery



Battery Technologies. Figure 22
Dynamic stress test by USABC [19]

systems. A common test adapted by manufacturers in the USA is known as the dynamic stress test (DST), developed by the United States Advanced Battery Consortium (USABC). Figure 22 shows an example of the battery charging and discharging power profiles that must be successfully followed to acquire DST conformation. The test can be performed at various temperatures to determine ideal operating conditions. The test is designed to gauge battery performance characteristics such as partial discharge and hold, sustained climb, thermal performance, and fast charge response. One such battery was tested by the Electric Power Research Institute (EPRI). Figure 23 shows DST results of that battery, specifically energy storage capacity versus number of DST test cycles at 80% depth of discharge. As shown, a 12.5% drop in capacity is attained after 3,000 cycles. This is in contrast to a 37% drop in capacity for NiMH batteries subject to a similar test [20]. Longer life expectancy combined with larger power density make lithium-ion batteries an ideal candidate for EVs.

Twenty watt-hours of energy storage capacity is lost after 3,000 charge–discharge cycles, as seen in Fig. 23.

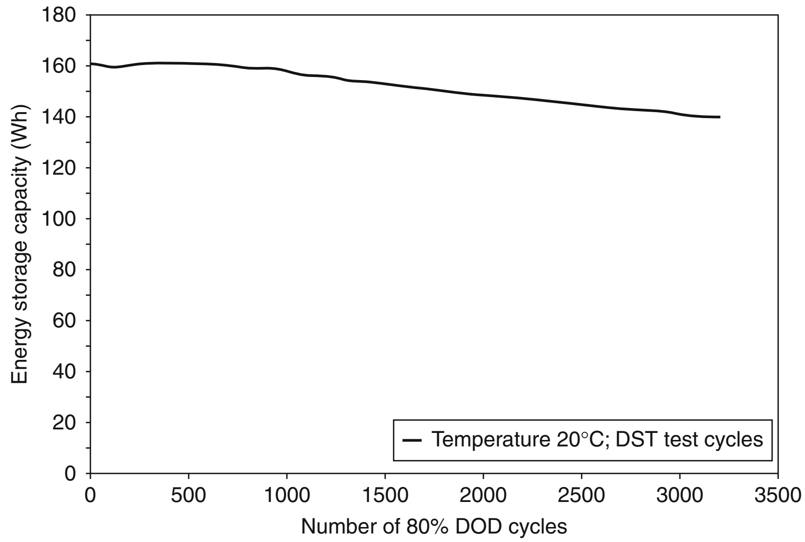
Thermal Runway

Thermal runaway (TR) is defined as a phenomenon where an increase in temperature creates conditions for further increases in temperature. Viable conditions for TR exist when a battery is producing more heat than it can dissipate. Thermal runaway can lead to leaks, venting of gas, and possibly a fire. According to Saft, temperature in a cell must be kept below 145°C to prevent conditions for TR from arising.

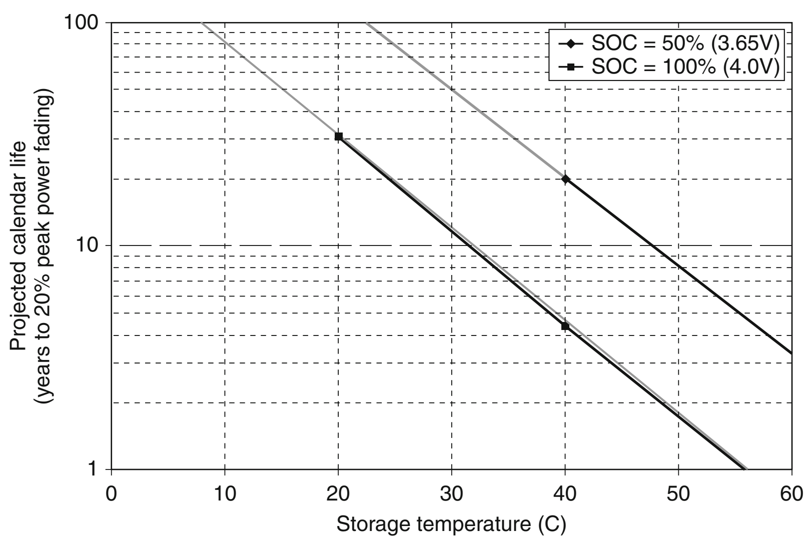
As battery temperature typically increases during operation, resistance of the ion-transferring electrolyte decreases. This leads to an increase in the current passing through the battery, raising the temperature of the battery even further. If the electrolyte becomes too hot, its resistance will become negligible and allow enough current to flow for chemical compounds on the cathode and anode to breakdown and short circuit.

Excessive ambient temperatures are another cause of TR, according to Saft. Computers, cell phones, and other portable devices are often subject to prolonged exposure to direct sunlight. Additionally, portable electronics could be operated in constricted spaces, with insufficient room for heat dissipation. High ambient temperatures can also harbor conditions for TR.

EPRI identifies overcharging as yet another source for TR [20]. Overcharging can lead to build up of lithium deposits that can penetrate the film separating the anode and the cathode, leading to a short circuit. All lithium-based batteries are equipped with protective circuitry to avoid overcharging. Failure of



Battery Technologies. Figure 23
DST results for Saft's lithium-ion battery [20]



Battery Technologies. Figure 24
Projected calendar life as a function of storage temperature [20]

protective circuitry can lead to build up of lithium-ions on the graphite anode, forming lithium dendrite. (Most metals are combined with alloys for dexterity and strength. Due to the presence of alloys, the metal tends to exist in a nonuniform, snowflake-like distribution called *dendrite.*) With increasing formation of this dendrite, useful anode surface area diminishes, leading to reduced battery capacity. If charging continues even further, the dendrite will penetrate the separator and react with the cathode, creating a short circuit. Metallic lithium is still at the developmental stage because it is prone to dendrite formation. Figure 24 depicts EPRI's projection of effects of storage temperature on battery life.

Irrespective of the cause, TR is a dangerous prospect. Potential large-scale use will require development of adequate prevention of conditions leading to TR [20]. USABC and EPRI have proposed various solutions, albeit with negative impacts on power density and capacity.

Capacity Fading

Capacity fading (CF) refers to reduction in battery capacity after repeated charge or discharge cycles. Yunjian et al. [21] uses a lithium-ion battery, with lithium manganese oxide ($LiMn_2O_4$) as cathode and graphite as anode to study capacity fading characteristics. Lithium hexafluorophospate ($LiPF_6$) is present as an electrolytic salt. The battery was charged to 4.2 V and then stored for a period of 96 h at 55°C. A notable reaction was the formulation of hydrofluoric acid (HF) and a consequent dissolution of manganese (Mn). The following reactions were noted:

$$LiPF_6 + 4H_2O \rightarrow PO_4{}^{3-} + LiF + 5HF$$

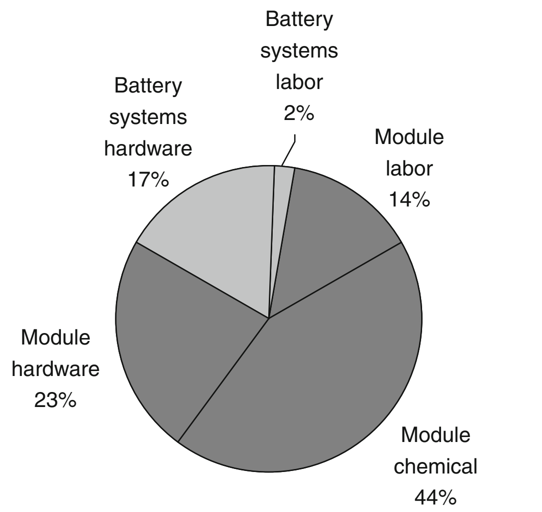
$$2LiMn_2O_4 + 4H^+ \rightarrow 3MnO_2 + Mn^{2+} + 2Li^+ + 2H_2O$$

Mn^{2+} enters the electrolyte and manganese dioxide (MnO_2) is deposited on the cathode. A reported 8 mAh/g of capacity was lost on the first day. Only 2 mAh/g of capacity was lost during each of following 3 days. MnO_2 formation on the cathode protected it from engaging in further dissolution of manganese (Mn), which explains the dwindling in CF. Charge retention of the battery was found to be 83.3%, 85.8%, 86.9%, and 88.6% for those 4 days.

Elevated temperatures can accelerate the rate at which CF occurs, as evident from work done by Xia et al. [22]. When operated above 65°C, the number of operational cycles is well below the EV requirement of 1,000–1,500. Degradation of electrode materials has been found to be the main reason for CF at high temperatures [22].

Cost

Lithium-based batteries are subject to aging even if not being used. Also, lithium batteries are dependent on protective circuits to maintain safe levels of voltage and

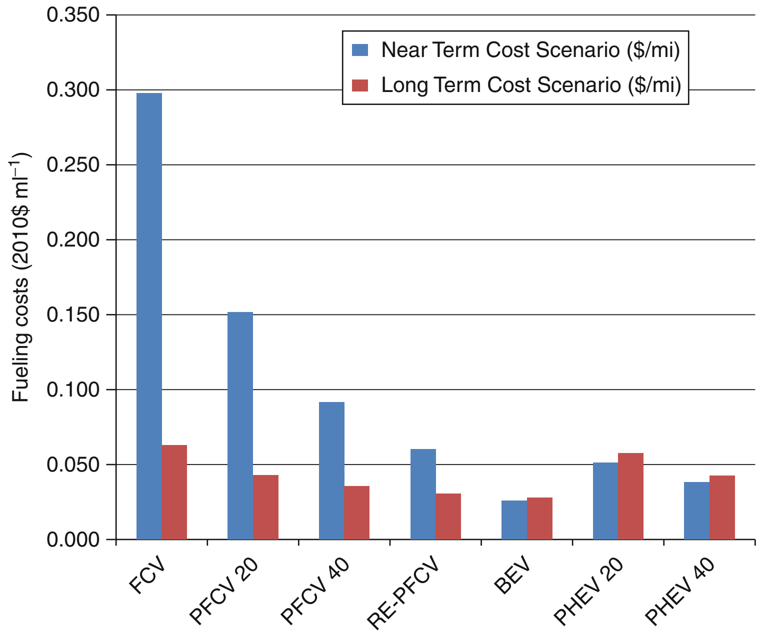


Battery Technologies. Figure 25
Component costs as percentage for Saft's EV lithium-ion battery [18]

current. These factors propagate into a 40% (average) higher manufacturing cost for lithium-based batteries compared to NiMH [20]. Figure 25 provides a breakdown of costs to manufacture an EV lithium-ion battery.

Several automotive manufacturers have announced plans to incorporate lithium-based batteries for use in HEVs, although NiMH batteries currently predominate. Lithium-ion batteries store more than twice as much energy per kilogram (250–400 Wh/kg) compared to the next-best battery technology, NiMH.

After having purchased their EV, customers are now responsible for operating costs for as long as they own the vehicle. Operating costs can vary based on battery capacity, efficiency, environmental conditions, and usage. Nevertheless, once gas savings balance out the cost of the EV, long-term savings in operating costs become apparent. A lab experiment conducted by EPRI in 2010 [23] employed various EV types, each with a lithium-ion battery system. Operating costs (loosely termed "fueling costs") are shown in Fig. 26. Here, the following EV types were used: Fuel Cell Vehicle (FCV), Plug-in Fuel Cell Vehicle (PFCV), Range Extender Fuel Cell Vehicle (FCV), Battery Electric Vehicle (BEV), and Plug-in Hybrid Electric Vehicle (PHEV). A "20" (or "40") in the name indicates 20 (or 40) miles on a full charge.



Battery Technologies. Figure 26
Operational costs per mile for various Li-ion EV configurations [23]

In the near term, FCVs are more expensive due to the cost of hydrogen. The FCV fitted with a range extender module uses considerably lesser hydrogen, as consistent with the lower near term operating cost. As expected, predominant battery use in EVs results in lower near term costs. In the long term, the difference in cost of hydrogen versus electricity became smaller, as apparent in the near identical long-term costs for all vehicle types.

To make lithium-ion batteries practical for mass-produced electric-drive vehicles, new technologies must increase the energy the batteries store and the speed with which they can discharge it. They must also lengthen cycle life to 15 years or 241,000 km (150,000 miles) – the average life of a vehicle [24].

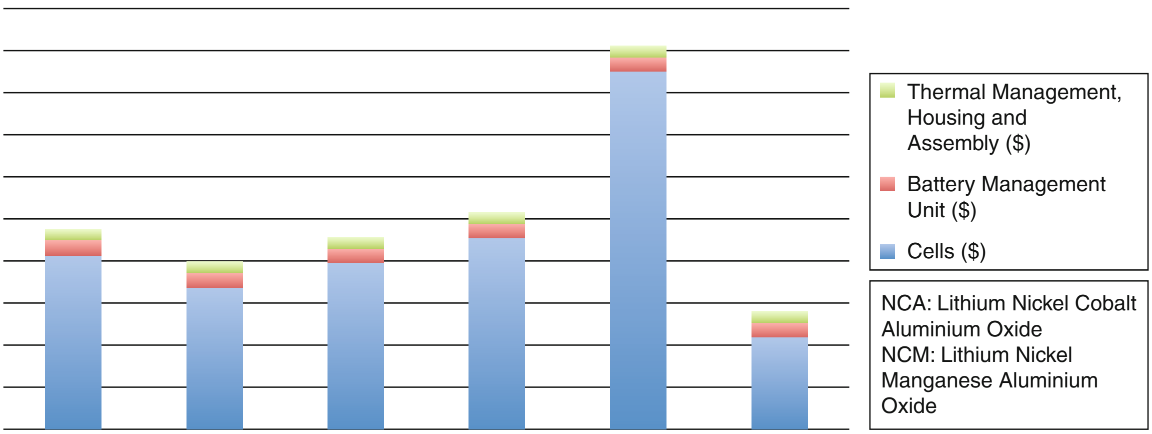
Perhaps it would be appropriate to compare lithium ion to other chemistries in terms of cost of a battery pack for EVs. Figure 27 provides such a comparison for a PHEV-40, as per 2010 cost estimates made by EPRI's Duvall et al. [23] and the Electric Auto Association.

Notably, Pb-A and NiMH (best case) appear to carry the lowest and highest overall costs respectively. It is important to mention that a typical EV lead acid battery pack only has a life of approximately 14–16 months (assuming the vehicle is driven 20–40 miles daily). On the other hand, the NiMH pack has a life span of roughly 5.5 years.

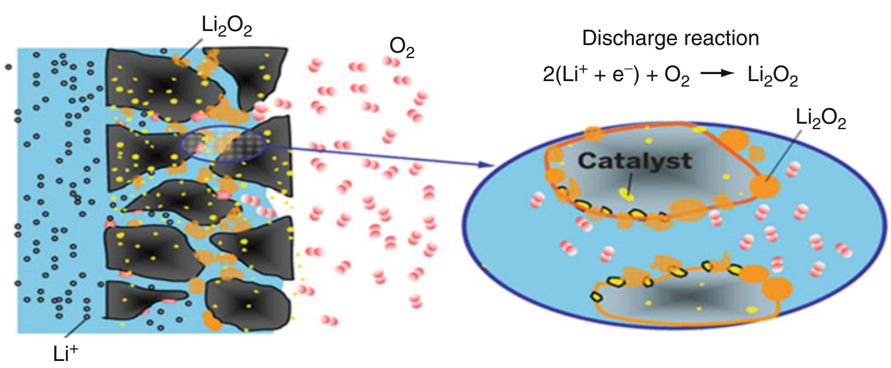
Metal–Air Batteries

Metal–air batteries get their name from their reactants which undergo electrochemical reactions to release energy. They are one of the most compact and potentially the least expensive batteries available. They are also environmentally friendly. However, their main disadvantage so far has been that electrical recharging of these batteries is very difficult and inefficient. Although many manufacturers offer units that can be refueled, where the consumed metal is mechanically replaced and processed separately, there still have not been many developers who offer rechargeable batteries. Rechargeable metal air batteries that are under production have a life of only a few hundred cycles and an efficiency of about 50% [1, 6].

Current research in lithium–air batteries have shown that they can provide an energy density of 1,700 Wh/kg, which is more than the energy density



Battery Technologies. Figure 27
Cost breakdown for complete battery pack used for typical PHEV40



Battery Technologies. Figure 28
Li–air battery [6]

of any other battery technology present today and is comparable to the practical energy density of gasoline [6] (Fig. 28).

Air electrodes and metal–air battery technologies have already been used in fuel cell systems. Earlier, zinc was the predominant metal used in metal–air batteries. Recently, lithium instead of zinc as the metal has started being used which has increased the energy output eightfold. As seen in the figure above, the lithium–air battery's porous carbon cathode (gray) is flooded with the electrolyte (blue). The Li^+ ions (small dots) react with oxygen molecules (pairs of dots) at catalyst sites (yellow) to form lithium oxides (orange). The oxygen electrode proceeding in tandem with lithium according to the reaction $2Li + O_2 \rightarrow Li_2O_2$ can deliver a capacity of 1,200 mAh/g. The first lithium–air cell was successfully assembled and discharged in 1996, but attractive rechargeability was demonstrated only recently [3].

It could be argued that such a system unites within the same device the two most prominent failures of battery and fuel-cell technologies, namely, the inability to master lithium and oxygen electrodes. These perceived issues have prevented the practical use of lithium–air batteries. Improving energy storage and preventing Li_2O_2 from clogging the electrode require a better understanding of the reaction mechanism of the oxygen electrode. Engineering and chemical

advances are also required to prevent the ingress of either CO_2 or H_2O, which could react with either Li_2O_2 or lithium metal [3].

Zinc Bromine Battery

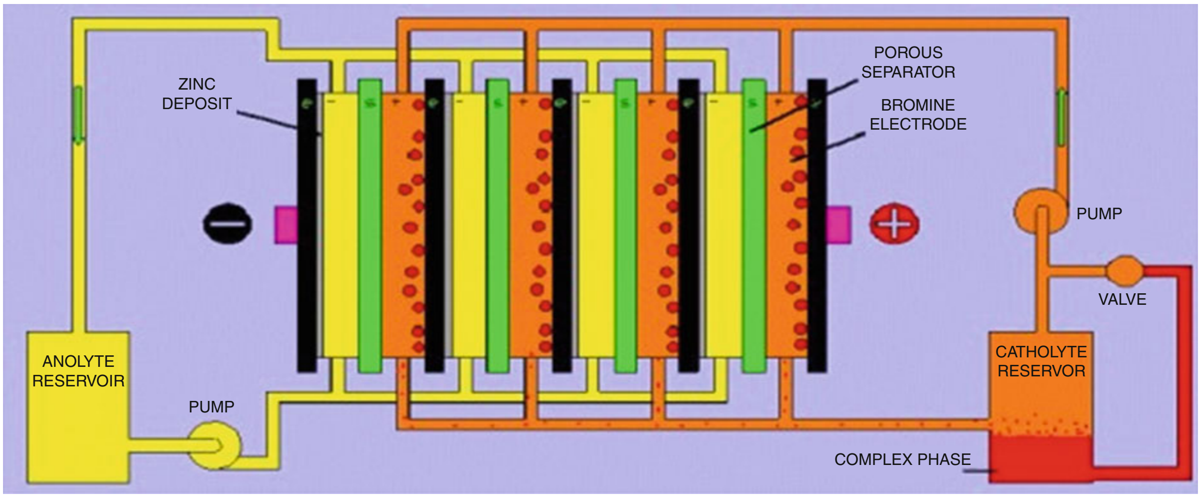
The zinc bromine battery is based on the chemical reactions between two commonly available materials, zinc and bromine. This battery was developed by Exxon in the early 1970s. It is a hybrid flow battery system since zinc is deposited on the negative electrode during the charge cycle. Unlike conventional flow batteries, the energy storage capacity of the zinc–bromine hybrid is constrained by the amount of surface area available for deposition [4, 9].

One of the main advantages of zinc–bromine batteries is that it can be fully discharged without any damage to the battery and has a life of at least 1,500 charge/discharge cycles. This battery is ideally suited in applications that require deep cycle and long cycle life energy storage. These batteries are made with low-cost, recyclable plastics and manufactured with techniques suitable for mass production and at low production costs [4].

As seen in the figure below, the battery consists of a zinc negative electrode and a bromine positive electrode separated by a microporous separator. An aqueous solution of zinc/bromide is circulated through the two compartments of the cell from two separate reservoirs. The electrolyte stream in contact with the positive electrode contains bromine which is maintained at the desired concentration by equilibrating with a bromine storage medium. The bromine storage medium is immiscible with an aqueous solution containing zinc bromide. All battery components are made from a bromine inert plastic [4] (Fig. 29).

During discharge, zinc is converted to zinc ion with the release of two electrons and bromine is converted to bromide, the zinc ion and bromine combine to form zinc bromide. The chemical process used to generate the electric current increases the zinc-ion and bromide-ion concentration in both electrolyte tanks. During charge, metallic zinc is deposited as a thin film on one side of the plastic electrode. Meanwhile, bromine is evolved as a dilute solution on the other side of the membrane, reacting with other compounds in solution (organic amines) to form viscous, dense bromine-adduct oil that sinks to the bottom of the tank. The bromine oil is allowed to mix with the rest of the electrolyte during discharge. The net efficiency of this battery is about 75% [9].

The zinc–bromine battery uses electrodes that do not take part in the reactions but merely serve as substrates for the reactions. Therefore, there is no loss of performance, as in most rechargeable batteries, from



Battery Technologies. Figure 29
ZnBr battery [4]

repeated cycling causing electrode material deterioration. When the zinc–bromine battery is completely discharged all the metal zinc plated on the negative electrodes is dissolved in the electrolyte and again produced the next time the battery is charged. In the fully discharged state the zinc/bromine battery can be left indefinitely [4].

The zinc–bromine battery has an energy density of 75–85 Wh/kg. The power characteristics of the battery can be modified for selected applications, making them extremely useful for multipurpose energy storage [4].

Supercapacitors

In the field of energy storage, two parameters are fundamental for storage devices: the energy density and the power charging and discharging rates. The first parameter defines the amount of energy that can be stored in a given volume. The lower the maximum charging and discharging rates, the more time that is required for loading and unloading the required amount of energy into the storage device. The ideal storage device should have both a high energy density together with high power charging and discharging rates. This is unfortunately not the case and compromises have to be made. Current battery technologies have relatively high energy densities but relatively poor power densities. Supercapacitors are a compromise between batteries and conventional capacitors. Their main characteristic is that they possess both a relatively high energy density and power density [25].

Integrating with an Onboard Energy Source for an EV

The integration of the onboard energy source for an electrically propelled vehicle with a supercapacitor bank (SB) as a peak power unit can lead to substantial benefits in terms of EV performances, battery life, and energy economy. An SB made up of single cells connected in series and in parallel, featuring appropriate parameters of energy density, power density, with high charging–discharging efficiency and affordable cost can be beneficial as a suitable device to support the energy source of an electric vehicle, thus providing optimized energy management [26].

The potential benefits of an integrated system SB-electrochemical energy source are the following:

- To improve the vehicle efficiency and energy economy over variable power driving conditions
- To assure high performance and good vehicle behavioral response independently from the status of the energy source (including age)
- To improve the endurance of the energy source to the extent of its dependence on the high rate power demand
- To extend the vehicle's range at full performance as a consequence of the combined effect of load leveling of the onboard energy source and of better efficiency of energy recovery

Second to the range of the EV, high acceleration performance is a highly desired feature to achieve integration with the majority of today's vehicles. The integration of an SB with a battery allows a system design optimized according to driving requirements, by making the specific power and specific energy parameters of the energy source independent of each other. As a consequence of this consideration, it will be possible to design the storage battery with respect to energy storage capability and life requirement without taking into account the power requirement [26].

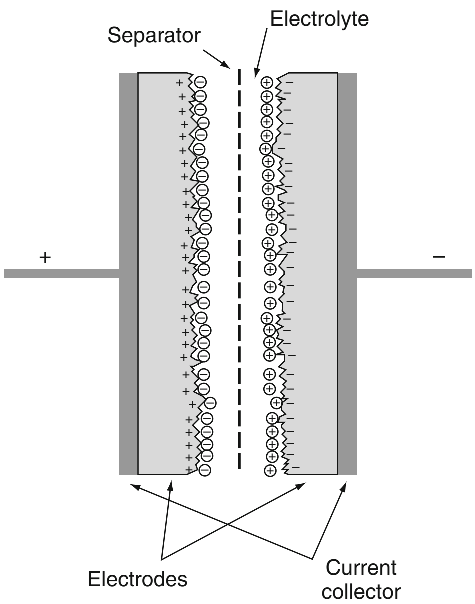
Difference Between Capacitors and Supercapacitors

A supercapacitor differs from a conventional capacitor both in the physical phenomena and the materials from which it is made. In today's supercapacitors, the dielectric is an electrolyte interposed between two electrodes. When a voltage is applied, a double layer of charges is formed at the interface between the electrodes and the electrolyte. In the case of supercapacitors, the distance between the charges corresponds to the thickness of the double layer, that is, only a fraction of a nanometer. This accounts for the difference in terms of capacitance per square centimeter between a conventional capacitor in the (order of magnitude nF/cm^2) and a supercapacitor (order of magnitude $50{,}000\ nF/cm^2$) [26].

The way to increase the energy stored in a conventional capacitor is to operate at high voltages (up to 3,000 V) consistent with the dielectric breakdown voltage. In today's supercapacitors, the voltage to be applied must be limited by either the solvent or the organic electrolyte decomposition voltage (1.23 V and

Battery Technologies. Table 9 Characteristics of supercapacitors based on the electrode and electrolyte material [26]

Electrode material	Carbon	Carbon	Metallic oxides
Electrolyte	Aqueous electrolyte	Organic electrolyte	Aqueous electrolyte
Maximum voltage (V)	1	3	1
Specific power (kW/kg)	0.8–2.6	1.5–5	0.5
Specific energy (Wh/kg)	0.2–1.3	3–6	1



Battery Technologies. Figure 30 Principle of supercapacitors [25]

3.5 V, respectively). In this case, the only way to increase the stored energy is to raise the capacitance value by adopting electrode materials with very high specific area. In particular, active carbon may reach, through suitable chemical processes, a specific area of 103 m^2/g, and a specific capacitance of 102 F/g. In addition, it is possible to reach very low values of the internal resistance that allows the device to provide high output power.

So far, only supercapacitors operating on the basis of charge separation phenomena due to the application of an external voltage between the electrodes have been considered. There is another type of supercapacitor, called pseudocapacitor, in which reduction and oxidation reactions occur during charge and discharge phases. The electrodes are made of metallic oxides (typically ruthenium or iridium) and electrolytes are liquid. The characteristics of supercapacitors are summarized as in Table 9 [26, 27].

Working Principle of a Supercapacitor

Supercapacitors are electrochemical double layer capacitors (EDLC). Their technology is similar to that of batteries, but the main difference is that they involve only electrostatic phenomenon (non-faradic). This is the first difference between batteries and supercapacitors. Their power density is higher because there are no chemical reactions during charging and discharging. Also, for this reason, charge storage in EDLCs is highly reversible, which allows them to achieve very high cycling stabilities. EDLCs generally operate with stable performance characteristics for many charge–discharge cycles, sometimes as many as 10^6 cycles. On the other hand, electrochemical batteries are generally limited to only about 10^3 cycles. In double-layer capacitors, the energy is stored by charge transfer at the boundary between electrode and electrolyte. The amount of stored energy is a function of the available electrode surface, the size of the ions, and the level of the electrolyte decomposition voltage [25].

Supercapacitors contain two electrodes, a separator and an electrolyte, as shown in Fig. 30. The two electrodes provide a high surface area, defining the energy density of the component. On the electrodes, current collectors with a high conducting part assure the interface between the electrodes and the connections of the supercapacitor. The two electrodes are separated by a membrane, which allows the mobility of the charged ions and forbids electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other. As the dissociation voltage of the electrolytes used is less than 3 V, this limits the maximum voltage that can be reached by the supercapacitor. Another disadvantage is lower ionic conductivity, which reduces the power capability [25].

The performance of an electrochemical double layer supercapacitor (EDLC) can be adjusted by changing the nature of its electrolyte. As mentioned earlier, an EDLC can utilize either an aqueous or organic electrolyte. Aqueous electrolytes generally have lower equivalent series resistance (ESR) compared to organic electrolytes. However, aqueous electrolytes also have lower breakdown voltages. Therefore, in choosing between an aqueous or organic electrolyte, one must consider the trade-offs between capacitance, ESR, and voltage. Because of these trade-offs, the choice of electrolyte often depends on the intended application of the supercapacitor [27].

While the nature of the electrolyte is of great importance in supercapacitor design, the subclasses of EDLCs are distinguished primarily by the form of carbon they use as an electrode material. Carbon electrode materials generally have higher surface area, lower cost, and more established fabrication techniques than other materials such as conducting polymers and metal oxides.

Electrode Materials Used in EDLC

Activated Carbon Activated carbon is the most commonly used electrode material in EDLCs. It is less expensive and possesses a higher surface area than other carbon-based materials. Activated carbons utilize a complex porous structure composed of different sized micropores (<200 nm wide), mesopores (200–5,000 nm) and macropores (>5,000 nm) to achieve high surface areas. Although capacitance is directly proportional to surface area, evidence suggests that, for activated carbons, not all of the high surface area contributes to the capacitance of the device. This discrepancy is believed to be caused by electrolyte ions that are too large to diffuse into smaller micropores, thus preventing some pores from contributing to charge storage [27]. Research also suggests an empirical relationship between the distribution of pore sizes, energy density, and power density of the device. Larger pore sizes correlate with higher power densities and smaller pore sizes correlate with higher energy densities. As a result, the pore size distribution of activated carbon electrodes is a major area of research in EDLC design. In particular, research has been focused on determining the optimal pore size for a given ion size and upon improving the methods used to control the pore size distribution during fabrication [27].

Carbon Aerogels There is an increasing interest in using carbon aerogels as an electrode material for EDLCs. Carbon aerogels are formed from a continuous network of conductive carbon nanoparticles with interspersed mesopores. Due to their continuous structure and their ability to bond chemically to the current collector, carbon aerogels do not require the application of an additional adhesive binding agent. As a result of this, carbon aerogels have lower ESR than activated carbons. (The internal components of the capacitor (current collectors, electrodes, and electrolyte) contribute to a resistance, which is measured in aggregate by a quantity known as the equivalent series resistance (ESR). The voltage during discharge is determined by this resistance.) The reduced ESR yields higher power and this is the primary area of interest in supercapacitor research involving carbon aerogels [27].

Carbon Nanotubes Electrodes made from this material are grown as an entangled mat of carbon nanotubes with an open and accessible network of mesopores. Unlike other carbon-based electrodes, the mesopores in carbon nanotube electrodes are interconnected, allowing a continuous charge distribution that uses almost all of the available surface area. Thus, the surface area is utilized more efficiently to achieve capacitance comparable to those in activated-carbon-based supercapacitors, even though carbon nanotube electrodes have a smaller surface area compared to activated carbon electrodes [27]. As the electrolyte ions can easily diffuse into the mesoporous network, carbon nanotube electrodes also have a lower ESR than activated carbon. In addition, several fabrication techniques have been developed to reduce the ESR even further. Carbon nanotubes can be grown directly onto the current collectors, subjected to heat-treatment or cast into colloidal suspension thin films [27]. The efficiency of the entangled mat structure allows higher energy densities [27].

Pseudocapacitors

In contrast to conventional EDLCs, which store charge electrostatically, pseudocapacitors store charge faradically through the transfer of charge between electrode and electrolyte. This is accomplished through

electrosorption, reduction–oxidation reactions, and intercalation processes. These faradic processes may allow pseudocapacitors to achieve greater capacitances and energy densities than EDLCs. There are two electrode materials that are used to store charge in pseudocapacitors, conducting polymers and metal oxides [27].

Electrode Materials Used in Pseudocapacitors

Conducting Polymers Conducting polymers have a relatively high capacitance and conductivity and a relatively low ESR and cost compared to carbon-based electrode materials [27]. In particular, the *n*/*p*-type polymer configuration, with one negatively charged (*n*-doped) and one positively charged (*p*-doped) conducting polymer electrode, has the greatest potential energy and power densities. However, a lack of efficient *n*-doped conducting polymer materials has prevented these pseudocapacitors from reaching their potential. Additionally, it is believed that the mechanical stress on conducting polymers during reduction–oxidation reactions limits the stability of these pseudocapacitors through many charge–discharge cycles. This reduced cycling stability has hindered the development of conducting polymer pseudocapacitors [27].

Metal Oxides Metal oxides like ruthenium oxide have high conductivity, which makes them a good electrode material for supercapacitors [27]. The capacitance of ruthenium oxide is achieved through the insertion and removal of protons into its amorphous structure. In its hydrous form, the capacitance exceeds that of carbon-based and conducting polymer materials. Furthermore, the ESR of hydrous ruthenium oxide is lower than that of other electrode materials. As a result, ruthenium oxide supercapacitors may be able to achieve higher energy and power densities than similar carbon electrode supercapacitors. However, despite this potential, the success of ruthenium oxide has been limited by its prohibitive cost. Thus, a major area of research is the development of fabrication methods and composite materials to reduce the cost of ruthenium oxide, without reducing the performance [27].

Composite Electrode Capacitors Composite electrodes integrate carbon-based materials with either conducting polymer or metal oxide materials and incorporate both physical and chemical charge storage mechanisms together in a single electrode. The carbon-based materials facilitate a capacitive double layer of charge and also provide a high-surface-area backbone that increases the contact between the deposited pseudocapacitive materials and electrolyte. The pseudocapacitive materials further increase the capacitance of the composite electrode through faradic reactions [27]. Composite electrodes constructed from carbon nanotubes and polypyrrole, a conducting polymer, have been particularly successful. This electrode is able to achieve higher capacitances than either a pure carbon nanotube or pure polypyrrole polymer-based electrode [27]. This is attributed to the accessibility of the entangled mat structure, which allows a uniform coating of polypyrrole and a three-dimensional distribution of charge. Moreover, the structural integrity of the entangled mat limits the mechanical stress caused by the insertion and removal of ions in the deposited polypyrrole. Therefore, unlike conducting polymers, these composites have been able to achieve a cycling stability comparable to that of EDLCs having carbon-based electrodes [27].

Model for Supercapacitors

A conventional model describing the supercapacitor modeled as an equivalent electrical circuit is useful for developments of applications where supercapacitors can be used. Figure 31, below, shows such a model.

The first parameter is the capacitance of the component. It defines the capacitive behavior of the supercapacitor and the energy that can be stored. This capacitance is not constant. It is dependent on the voltage across and is the reason why the capacitance of the supercapacitor is modeled as a constant capacitor C_o, with a parallel capacitor C_v, which has a linear dependence on the voltage V [25].

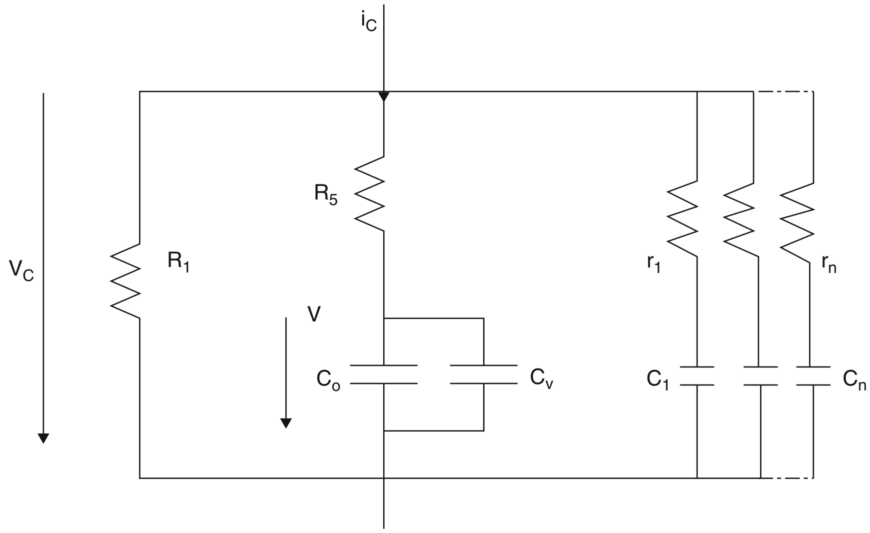
$$C = C_o + C_v, \text{ where } C_v = K \bullet V \tag{3}$$

This defines the capacitance C of the component.

Following this definition, the current capacitance can be derived from (3).

$$Q = CV$$

$$I_c = dQ/dt$$



Battery Technologies. Figure 31
Equivalent circuit model for supercapacitors [25]

Battery Technologies. Table 10 Energy capability versus the capacitance [25]

Capacitance	C = 1,800 F	W = 5,625 J	
Current capacitance	C_i = 2,100 F	W_i = 6,562 J	+16.65% increase
Energy capacitance	C_w = 1,850 F	W_w = 5,781 J	+2.77% increase

Therefore,

$$I_c = (C_o + 2K \bullet V)dV/dt \quad (4)$$

$$\text{Currentcapacitance } C_i = C_o + 2K \bullet V$$

Similarly, energy capacitance can also be defined.

$$\text{Power (P)} = I_c \bullet V = (C_o + K \bullet V^2)dV/dt \quad (5)$$

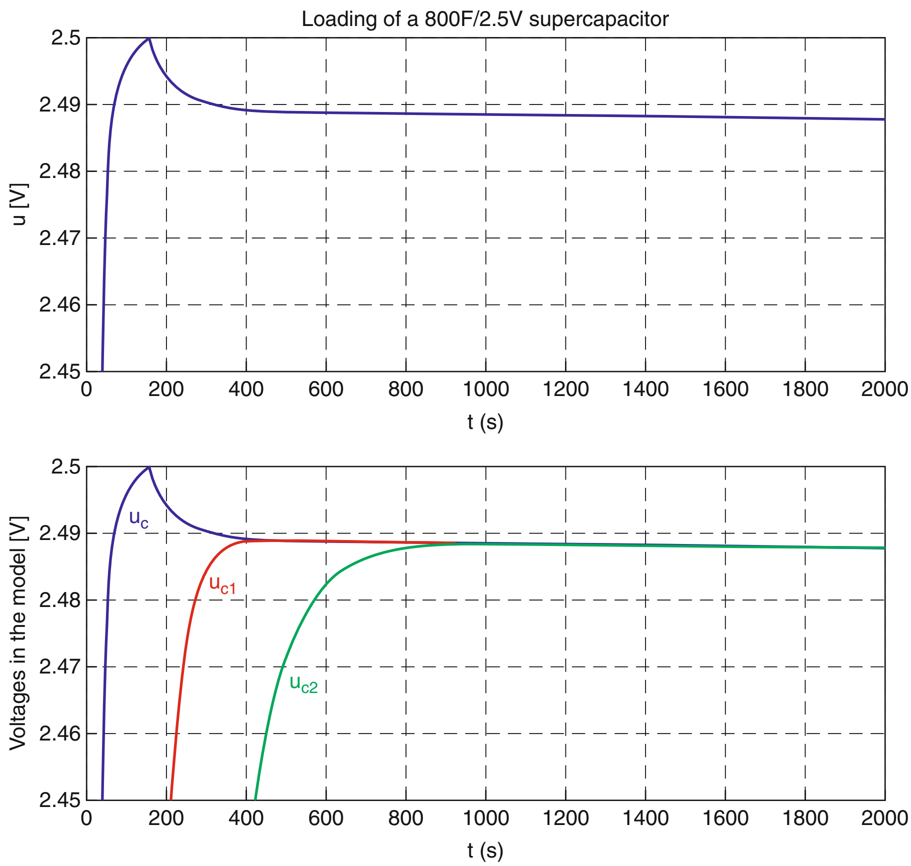
$$\text{Energy } (W_w) = \tfrac{1}{2}(C_o + 4/3(K \bullet V))V^2 \quad (6)$$

$$\text{Energycapacitance } (C_w) = C_o + 4/3(K \bullet V) \quad (7)$$

The amount of energy that can be stored into a supercapacitor can be expressed as a function of the capacitance that is considered. This is summarized for a 1,800 F/2.5 V supercapacitor, where measurements for C = 1,800 F and K = 150 F/V in Table 10.

The current capacitance C_i shows that it is possible to store 16.55% more energy than expected considering only the constant capacitance given by the manufacturer. Another consequence of this voltage-dependent capacitance is that the voltage will not increase linearly during the charge with a constant current. Two other parameters are conventional for a supercapacitor model. The first one is the series resistor R_s that induces voltage drops during charge and discharge. Its value influences the energy efficiency of the component and its power density. The second conventional parameter is the leakage resistor R_l that induces load losses when the component is in a standby mode. However, this resistor is not the only parameter that influences the voltage variation across a supercapacitor between a charge and discharge operation. This is illustrated in Fig. 32 [25].

The upper curve shows the typical voltage variation V_c across a 800 F/2.5 V supercapacitor during the end of its charge with a constant current. Once the charge is ended, the voltage decreases rapidly. This could be due to the leakage resistor but this is not strictly the case if the model in Fig. 31 is considered again. It makes n parallel RC circuits appear. This is illustrated in the lower part of Fig. 32 where the relaxation phenomena are presented as the charge of RC circuits with different constant times. The result is a decrease of the main



Battery Technologies. Figure 32
Relaxation phenomena [25]

voltage, not due to a dissipative component, but due to a homogenous arrangement of the loads and ions on the electrodes and in the electrolyte. Once all the voltages across all the equivalent capacitors are equal, then relaxation phenomena are supposed to be ended. The decrease of the main voltage is then linked to a leakage current. An ideal supercapacitor model should propose an infinite number of RC branches. For practical reasons linked to measurement, most of the models identify only two or three of these equivalent subcircuits [25].

Sizing Method of a Supercapacitive Tank

For a supercapacitor, the total amount of energy W_M that can be stored is expressed as a conventional capacitor:

$$W_M = \tfrac{1}{2}(C \bullet V_M{}^2) \tag{8}$$

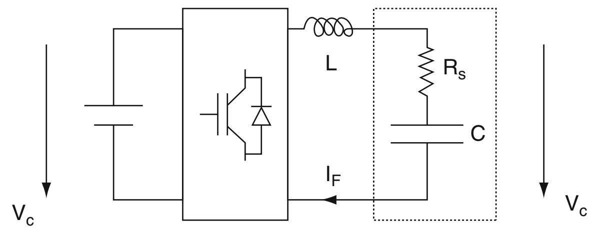
where C is the capacitance of the component and V_M is the maximum voltage. The voltage across the component has to be decreased from its maximum allowed value to 0 V for the use of the total amount of stored energy. This is not possible because the current provided by the supercapacitor should be infinite. For this reason, the minimum voltage when discharging the component has to be limited and all the energy stored in the component is not used [25]. It is then necessary to define the parameter d, which is the ratio between the minimum allowed voltage V_m for the discharging, and the maximum voltage V_M that defines a full charging of the component. d is expressed in percent and is called the discharge voltage ratio:

$$d = (V_m/V_M) \bullet 100 \tag{9}$$

Under this condition, the usable energy W_v that a supercapacitor can provide is given by the equation:

Battery Technologies. Table 11 Sizing of a supercapacitor tank

N_s	d (%)	Volume (m^3)	Weight (kg)	E (kWh)
4,872	50	1.46	1,943	7.6
5,709	60	1.71	2,283	8.92
7,164	70	2.15	2,865	11.2



Battery Technologies. Figure 33 Interfaces for supercapacitors [25]

$$W_v = W_M\left(1 - (d/100)^2\right)^2 \tag{10}$$

If d = 50%, the voltage is half of the maximum voltage at the end of the discharge, then the usable energy W_v will be 75% of the total stored energy W_M. For a given usable energy, the last two equations can be combined to identify the number of supercapacitors in the supercapacitor bank.

$$N_s = 2W_v/CV_M{}^2\left(1 - (d/100)^2\right) \tag{11}$$

Let us take an example where the supercapacitor is 1,800 F/2.5 V and the usable energy $W_u = 0.55$ MJ = 5.7 kWh. The corresponding sizing of a supercapacitive tank is given for three different values of d according to (10) and this supercapacitor in Table 11 [25].

$$W_v = 0.55\text{MJ}, C = 1800, FU_M = 2.5, VI_M = 200\text{A}$$

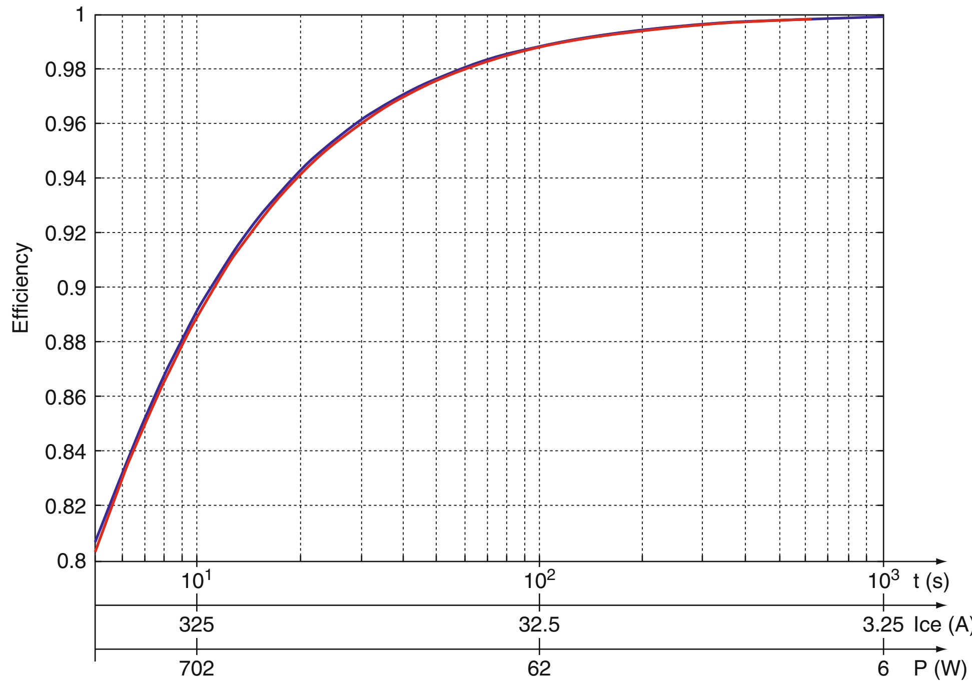
The best choice should define a SB with d = 50% because of the reduced number of supercapacitors and because the usable energy W_v is 75% of the maximum stored energy W_M. On another hand, the choice of N_s = 7,164 (d = 70%) leads to a strong oversizing of the SB where the usable energy W_v is only 51% of the maximum stored energy. This offers an interesting versatility in the management of the energy that has to be provided. If that tank and its associated power converters are designed for d = 70%, it will be possible to vary the voltage more than that limit in case of stronger random power constraints [25].

Energy Efficiency and Power Availability

One of the main parameters of a supercapacitor is its series resistance. Independent of voltage falling during charge and discharge, internal losses are due to this element. Even if manufacturers succeed in reducing the value of the series resistor, its value induces an energy efficiency lower than unity with the consequence of a reduction of the power availability [25].

The energy efficiency of supercapacitors is taken into consideration while sizing a supercapacitive tank because the way supercapacitors are charged and discharged influence their performance. One of the only ways to control the charging/discharging process is to develop power electronics interfaces in order to control the current for loading/unloading the supercapacitors [25]. This is illustrated in Fig. 33. The charge of supercapacitors is realized with a constant current, as shown in Fig. 34, where supercapacitors are loaded from a dc voltage source. The charging/discharging current is adjusted to maintain the product of $v_c I$ constant. The value of the charging/discharging current or power will define the energy efficiency of the supercapacitive tank together with the value of the equivalent series resistor. This is illustrated in Fig. 35 where the voltage discharge ratio d is 50%. In this case, 75% of the total used energy is loaded and unloaded for a 2,600 F/2.5 V/0.7 mΩ supercapacitor. The energy efficiency is presented versus the time, the current, or the power needed for loading/unloading the component [25].

The time for loading energy is chosen to be 10 s. Its energy efficiency is expected to be over 90%. This means a charging current limited to 320 A or a charging constant power limited to 700 W. The same can be applied to the current or the power during discharge. The constant power has to be kept lower than 420 W to obtain more than 90% energy efficiency. This has a consequence on the power density of the component



Battery Technologies. Figure 34
Charging characteristics [25]

which is 4,300 W/kg. Taking into account the energy efficiency, the power density will only be 806 W/kg if the energy efficiency is to be kept higher than 90%. This leads to an increased number of supercapacitors for the design of a storage tank. Therefore, the energy efficiency and the power availability both have to be taken into account for the design of a supercapacitor storage bank. The final parameter to be taken into account is the efficiency of the power converter needed for interfacing the supercapacitors with their load [25].

Power Train System Architecture

Architecture conceived with the electronic interface between the SB and the traction battery are shown in Fig. 36 below.

The main characteristics of this architecture are:

- The DC-to-DC converter has to be dimensioned for the maximum power flow into and out of the SB [26].
- The SB voltage may be kept always lower than the minimum traction battery voltage. As a consequence, a simpler DC-to-DC converter design may be obtained. The DC-to-DC converter may operate only in step-up mode during the traction phase and only in step-down mode during the braking phase [26].
- A lower operating voltage implies a lower number of cells connected in series and a reduced complexity of the electronic module of the SB [26].
- The possibility to add an auxiliary generator (auxiliary power unit) configuration without modifying the existing structure [26].

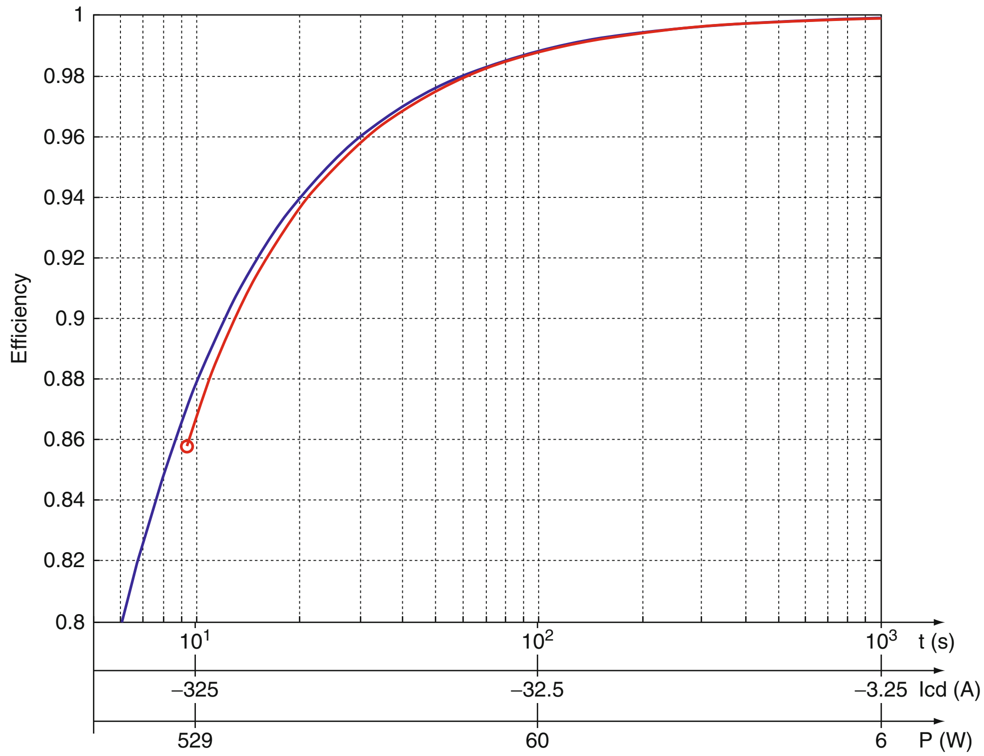
Future Developments in Supercapacitors

Currently, there is work in progress on the development of supercapacitors using solid dielectrics.

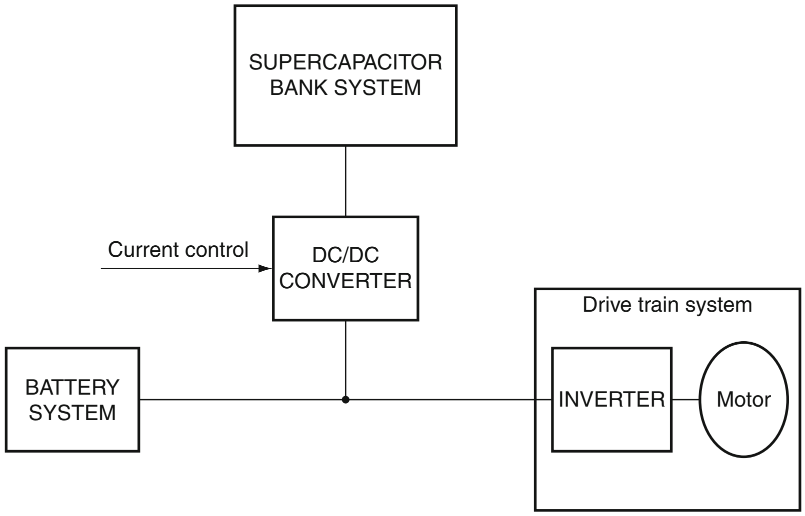
The energy density stored in a capacitor is given by:

$$W = \frac{1}{2}\varepsilon_o \varepsilon_r E^2$$

ε_o is the dielectric constant of free space, ε_r is the relative dielectric constant, and E is the electric field strength. Relative dielectric constants of 200,000 have been measured for 500 nm particles of $BaTiO_3$ coated with 5 nm



Battery Technologies. Figure 35
Discharging characteristics [25]



Battery Technologies. Figure 36
Powertrain architecture with DC/DC converter and series supercapacitor bank series connected [26]

of SiO_2 [28]. If these particles can be fabricated into supercapacitors with breakdown electric field strengths of the order of the breakdown strength of SiO_2, around 6×10^6 V/cm, then energy densities of the order of 100 KJ/cm^3 may be possible. If very high energy densities are achieved, these supercapacitors may replace batteries in EVs. There are a variety of materials with which very high dielectric constants can be obtained but there is a great deal of work to be done before these supercapacitors become available for EVs [28].

Recommendations for Future Work

Various applications and options discussed in this entry are still in the development phase and therefore are not "grid-ready." Current progress in the energy storage sector is limited to fulfillment of functional specifications only. Grid storage solutions are a long term goal for this sector. To develop these solutions, short-term goals need to include fundamental research, analysis, testing, evaluation of risk, and demonstration of technology. Table 12 is considered a starting point for the fulfillment of short- and long-term goals.

Battery Technologies. Table 12 Recommendations for future work

Action	Short term	2011–2013	2012–2016	2015–2020
Develop value propositions for storage to enable more renewable integration	Conduct assessment of utility and private renewable integration	Simulation and cost-benefit analysis of renewable plants and private systems	Large-scale demonstrations	Value and risk of renewable integration verified by the utility and understood by the end user
Development and enforcement of regulations	Develop target for development of regulations to address issues and risks associated with storage systems	Persistent enforcement of regulations in all types of regions (high and low renewable concentration)	Monitor progress of regulations and provide feedback for improvement in methodologies of local utility	Identification and continued enforcement of key regulations
Scenario modeling	Develop models for accurate forecasting of resource accessibility, demand, dispatch capabilities, pricing, and reliability	Identify incremental (smart grid, nuclear) and detrimental (EV, storage) technologies, in terms of grid operational risk	Demonstration of effects of best- and worst-case scenarios on supply/demand, technological development, and capital costs	Identification of relevant scenarios that will help guide the future development of potential storage technologies
Contribution: utility and public	Development of customer and utility actions for propagation of the renewable agenda	Assessment and regulated enforcement of utility enforced actions (e.g., price incentive for customers, storage management)	Assessment of potential customer actions (e.g., use of energy efficient devices)	Identification of low-risk actions for the utility and the customer
Reliability assessment	Develop current, short- and long-term assessment roadmap for risks associated with storage integration	Identify key factors affecting reliability of storage systems (e.g., variability, ramping requirements, peak mismatch)	Develop plan to proportionally increase integration of low-risk storage systems, with increasing demand, to achieve higher base-load penetration	Studious development of reliability risks and solutions for potential storage technologies

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Bicycle Integration with Public Transport

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Article Outline

Glossary

Bike lane A special road lane reserved for bikes only, usually about 4–6 ft wide, normally located on the right-hand side of the road.

Bike locker A box-like metal or plastic container for secure bike storage, often at rail stations, usually rented on a monthly basis.

Bike rack A device on which bikes can be mounted for transport (on buses) or attached for storage and security (on sidewalks).

Bike station Full-service, secure bike parking facility, usually providing repair and rental services, accessories, and touring advice.

Bus Motorized coach services providing communal transport on roads, usually in mixed traffic, but sometimes as part of special bus rapid transit (BRT) systems with separate rights of way.

Light rail Type of rail system similar to streetcars (trams) but often with separate right of way over at least part of its route, special boarding stations, and pre-paid fares.

Metro Urban rail system with separate rights of way, frequent service, and high carrying capacity, usually found only in large cities.

Public transport/transit General term for communal transport in cities, including buses, trams, trolleys, light rail, metros, suburban rail, ferries, and funiculars.

Suburban rail Short-distance passenger rail systems connecting large cities with their surrounding metropolitan areas, with longer distances between stops and less frequent service than metro systems.

Definition of the Subject and Its Importance

Coordinating bicycling with public transport is mutually beneficial, enhancing the benefits of both modes and encouraging more bicycling as well as more public transport use. Bicycling supports public transport by extending the catchment area of transit stops far beyond walking range and at much lower cost than neighborhood feeder buses and park-and-ride facilities for cars. Access to public transport helps cyclists make longer trips than possible by bike. Transit services can also provide convenient alternatives when cyclists encounter bad weather, difficult topography, gaps in the bikeway network, and mechanical failures.

Introduction

The overall importance of both bicycling and public transport in northern Europe has provided a strong rationale for coordinating these two modes of urban transport in recent decades [1]. European studies find that coordinating bicycling with public transport is mutually beneficial, enhancing the benefits of both modes and encouraging more bicycling as well as more public transport use [2–8]. In the Netherlands, 35% of all rail passengers reach their stations by bike – compared to 25% in Denmark and 9% in Sweden [1].

The main form of bike-transit integration in Europe is bike parking at suburban train and metro stations [1]. In the Netherlands, there are 350,000 bike parking spaces at train stations. German cities also have extensive bike parking at rail stations. The City of Berlin, for example, has over 32,000 bike parking spaces at its metro and suburban rail stations [9]. By comparison, no city in North America has more than 15,000 bike parking spaces of any kind, let alone at public transport stops.

The most impressive bike-and-ride facilities in Europe are state-of-the-art “bike stations,” which

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provide secure, sheltered parking as well as a wide range of services such as bike repairs, accessories, washing, rentals, and travel advice. In 2007, there were 67 bike stations in the Netherlands, 70 in Germany, and 20 in Switzerland, almost always located adjacent to train stations to facilitate bike-and-ride [1, 5, 10–12]. As noted later in this entry, there are only ten bike stations in all of North America, and they are much smaller than those in Europe.

North America obviously lags behind Europe in the integration of bicycling and public transport. In the past, bike-and-ride in North America was limited by low overall levels of cycling and public transport use in most cities, just the reverse of the situation in northern Europe [1, 5, 12, 13]. In recent years, however, both cycling levels and public transport use have risen sharply in the USA and Canada, and bike-and-ride trips have been increasing as well. Indeed, in some cities it has been so successful that the demand for bike-and-ride facilities exceeds the available supply [14, 15].

This entry describes the programs and policies currently being implemented in North America to integrate bicycling with public transport. It starts off with a brief overview of the various kinds of integration and the extent of their implementation. Most of the entry, however, is devoted to case studies of bike-transit integration in two large cities in Canada (Toronto and Vancouver) and six large cities in the USA (San Francisco, Portland, Minneapolis, Chicago, Washington, DC, and New York City). The case study analysis compares the type and extent of integration measures undertaken in the various cities, noting the strengths and weaknesses of each city's integration policies. The entry concludes by identifying the most innovative and successful policies in the eight cities and offers policy recommendations for future improvements.

Trends in Bike-Transit Integration

In recent years, levels of cycling and public transport use have reached record highs in both the USA and Canada. In 2008 public transport use in the USA was at its highest level since the early 1960s [16, 17]. Between 1995 and 2008, public transport trips rose by 38% in the USA and by 46% in Canada [17, 18]. Similarly, levels of cycling have increased considerably since 1990. In the USA the total number of bike trips to work increased by 32% from 1990 to 2005–2007 (averaged) [19, 20]. Over the shorter period 1996–2006, the number of bike trips to work in Canada rose by an even larger 42% [21].

While rising public transport use and increased cycling have provided the rationale for more bike-transit integration, federal funding in the USA has provided the necessary financing for a wide range of projects implemented in recent years at the state and local government levels [14, 15, 22, 23]. Indeed, the federal government finances some categories of bike-transit integration projects with an especially high 95% federal share. The integration of public transport with cycling has been endorsed by the Federal Transit Administration, the Federal Highway Administration, and the Transportation Research Board [14, 15, 24]. The Transport Association of Canada [25] and Transport Canada [26] have also endorsed bike-transit integration, but there is no federal funding for urban transport in Canada. There is no federal funding for urban transport in Canada, but provincial and local governments have provided large increases in funding for public transport and bicycling in recent years, including projects aimed at better integration [27, 28].

As documented in this entry, virtually every large city in the USA and Canada has been undertaking a range of measures to promote bike-and-ride. There are five main categories of measures to promote bike-transit integration:

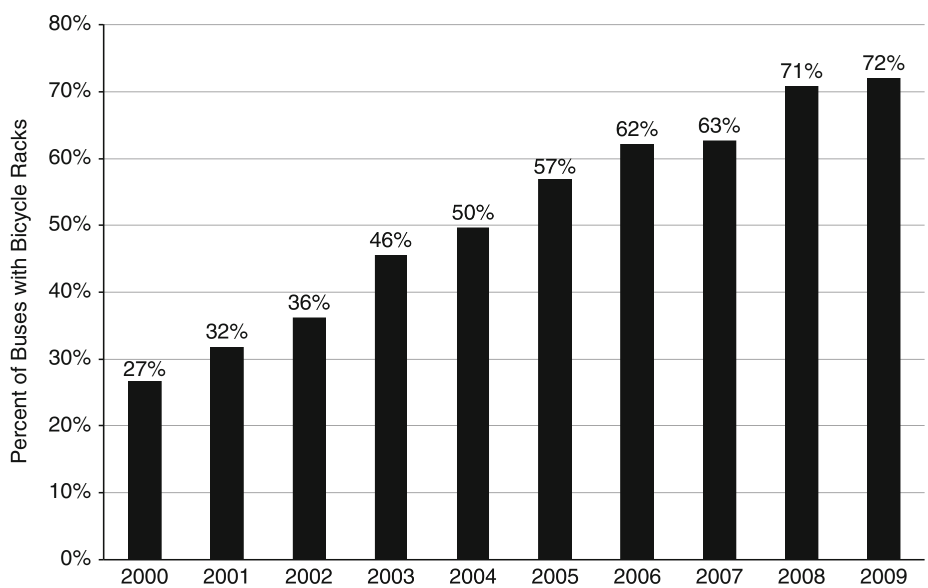
(a) Provision of bike parking at rail stations and bus stops, with different degrees of shelter and security
(b) Multifunctional bike stations providing not only parking but also a range of services such as bike rentals, repairs, parts and accessories, bike washing, showers and lockers, and touring advice
(c) Bike racks on buses, usually exterior, but occasionally interior storage
(d) Bikes on board vehicles, usually rail vehicles, sometimes with special bike racks, hooks, or even bike cars on trains
(e) Bike paths, lanes, and on-street routes that lead to public transport stations and stops, thus facilitating the bike's role as feeders and collectors for public transport

Extent of Bike-and-Ride Facilities in North America

The only available national statistics on bike parking at public transport stops are from recent surveys of 272 American and Canadian transit systems by the American Public Transportation Association [29, 30]. In the USA, the supply of bike parking spaces in 2008 was 24,178 at rail stations, 9,005 at bus stops, and 176 at ferry terminals. For the same year, Canadian systems reported 2,892 bike parking spaces at rail stations and 481 at bus stops. Between 2006 and 2008, the supply of bike parking increased by 67% in Canada and 26% in the USA [29, 30]. That is impressive progress, but it is striking that in 2008, the total supply of bike parking at public transport systems in the entire USA was only slightly more than the 32,000 spaces in Berlin, Germany [9].

Not only is there much less bike parking in North America, but it is far less likely to be sheltered and/or guarded. Throughout northern Europe, there has been a trend toward sheltered, guarded bike parking, usually outdoors but increasingly in bike stations [1, 5, 9, 12, 31, 32]. By comparison, unattended bike lockers are the main form of secure bike parking at North American public transport stops. Of the 56 large American and Canadian transit systems surveyed by the Transportation Research Board [15], 14 systems provided bike lockers at some of their rail and bus stops, but the actual number of lockers was not reported. The same TRB survey reported eight staffed bike parking stations in 2005, mainly on the West Coast. A few more bike stations have opened since then [10].

By far the most important form of bike-transit integration in North America is bike racks on buses. Indeed, on this dimension, North America is far ahead of Europe, where very few buses come equipped with bike racks. That is not surprising since 60% of all public transport trips in the USA are by bus [18]. Bike racks are inexpensive to install, easy to operate, and do not take up space on the vehicles themselves [15]. The 2005 TRB survey found that systems throughout the USA and Canada provide bike racks on buses, and that most systems have eliminated fees they had previously charged for rack use. As shown in Fig. 1, the percentage of buses with bike racks almost tripled in the USA in only 8 years, from 27% in 2000 to 72% in 2009 [30, 33]. Since 60% of all public transport trips in the USA are by bus, it is understandable that the focus of bike-transit integration efforts in North America has been on bus-bike racks [18, 33]. They are inexpensive to install, easy



Bicycle Integration with Public Transport. Figure 1
Trend in percentage of buses with exterior bicycle racks in the USA, 2001–2009 [18]

to operate, and do not take up space on the vehicles themselves [15].

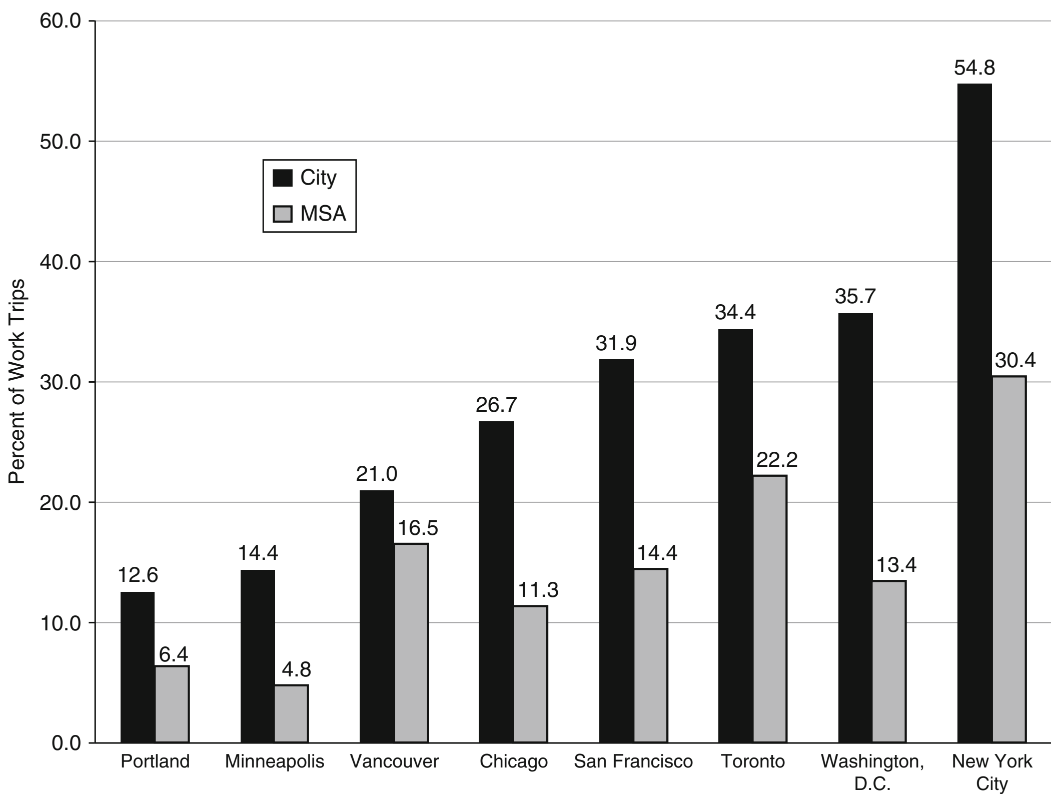
Another important form of bike-transit integration is the permission to take bikes on board public transport vehicles, since that enables cyclists to ride their bikes to and from public transport stops at both ends of their trips. Few public transport systems permit bikes to be taken on board buses unless they are compact, folding bikes. But most systems permit bikes on light rail, metro, and suburban rail trains, except during peak hour periods when crowding makes this infeasible [15]. Moreover, an increasing number of public transport systems are providing special accommodations for bikes on trains, such as bike racks, bike hooks, special bike holding areas near the doors, and even special bike cars – although rarely [15, 33].

The last aspect of bike-transit integration is the coordination of bike routes with public transport stops. There are no national statistics available on the extent of implementation, and it would be hard to quantify at any rate. Nevertheless, the eight case studies qualitatively assess this aspect of bike-transit integration in each of the cities.

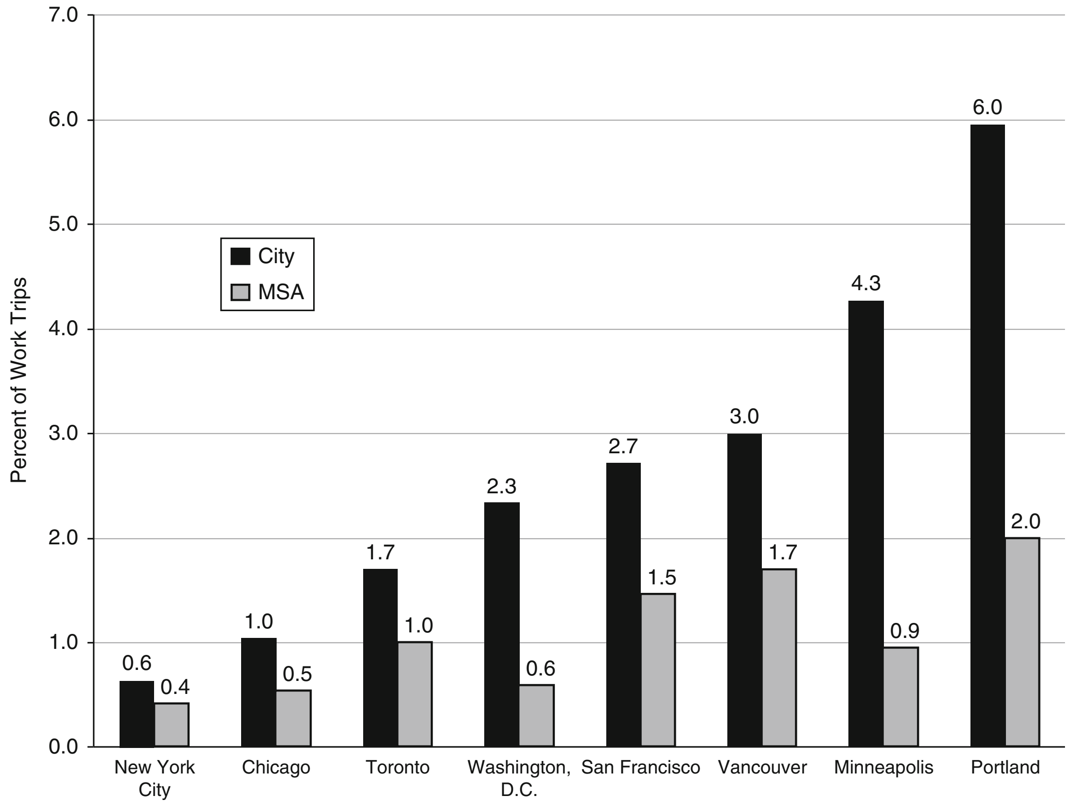
Case Studies of Bike-Transit Integration

All eight of the case study cities are large, but they vary considerably in metropolitan area population, ranging from 2.2 million in Portland, Oregon, to 18.2 million in New York City. The cities also vary widely in their geographic locations, climate, and topography. Most important for this study, they vary greatly in the share of trips covered by bicycling and public transport, as shown in Figs. 2 and 3.

In 2006, public transport shares of work trips for central city residents ranged from only 13% in Portland to 55% in New York (Fig. 2). Public transport trip shares for metropolitan areas ranged from 5% in



Bicycle Integration with Public Transport. Figure 2
Public transportation share of work trips in US and Canadian cities and metropolitan areas, 2006/2008 [20, 34]



Bicycle Integration with Public Transport. Figure 3
Bicycling share of work trips in US and Canadian cities and metropolitan areas, 2006/2008 [20, 34]

Minneapolis to 30% in New York. The Canadian cities of Vancouver and Toronto have relatively high public transport use for their intermediate size. Indeed, their metropolitan areas have higher public transport mode shares than the Chicago area. Other studies confirm that, controlling for population size, Canadian cities have slightly more than twice as many public transport trips per capita as American cities [35, 36]. Without exception, public transport use is higher in all eight central cities than in their suburbs. The difference is far smaller in Toronto and Vancouver than for the American cities, because of the higher density of Canadian suburbs as well as the greater provision of public transport services there [35, 36].

Levels of cycling also vary greatly among the eight cities (Fig. 3). Portland (6.0%) and Minneapolis (4.3%) had the highest bike mode shares of work trips in 2006, but Vancouver (3.0%) and San Francisco (2.7%) were not far behind. By comparison, cycling to work in New York (0.6%) and Chicago (1.0%) is rare. Similar to levels of public transport use, bicycling is much higher in central cities than in the suburbs. The differences for Canadian cities, however, tend to be smaller than for American cities, and the reason, again, is the much higher density of Canadian suburbs vis-à-vis American suburbs [28].

There are no comparable statistics on levels of bike-and-ride in each of these cities, since the most recent American and Canadian national travel surveys only report the main mode of transport for the work trip. Figures 2 and 3 provide useful background, however, by portraying the overall levels of cycling and public transport in the eight cities and their corresponding metropolitan areas. On the basis of European experience, it would seem that the higher the levels of both cycling and public transport use, the greater the potential for bike-transit coordination. On the other hand, where there are large imbalances between the two modes, it

might suggest that the modes substitute for each other rather than complement each other. For example, the extremely low level of cycling in New York might be partly due to a high level of public transport use. Conversely, Portland and Minneapolis, the cities with the highest bike mode shares, have the lowest public transport mode shares, suggesting that some bike trips might substitute for public transport trips. There are many possible explanations for the different levels of cycling and public transport use, but a detailed analysis is beyond the scope of this entry, which is limited to the more modest goal of examining the nature and extent of bike-and-ride programs in these eight case-study cities [1, 4, 5, 7].

Efforts to integrate cycling with public transport vary greatly among the eight case studies. New York City, for example, has done little to promote bike-and-ride, while San Francisco, Vancouver, and Portland have implemented the entire gamut of integration measures. The following section highlights the most important aspects of bike-and-ride policies in each city, noting in particular the strengths and weaknesses of current policies.

Unless otherwise indicated, the information for these case studies was obtained by the authors directly from bicycling planners, public transport systems, metropolitan planning organizations, city transport departments, and nongovernmental cycling and sustainable transport organizations in each metropolitan area. The same panel of transit and cycling experts also reviewed the case studies of their cities at several stages to check for accuracy, consistency, and completeness.

San Francisco

The San Francisco Bay Area has been a leader in bike-transit integration efforts in North America. Its regional metro system Bay Area Rapid Transit (BART) provides bike parking at almost all 43 stations, with a total of 4,313 bike parking spaces in 2009, including 1,010 in secure bike lockers. In order to increase convenience and flexibility, BART has been introducing electronic bike lockers (294 as of 2009), which are available on a first-come, first-serve basis and do not require advance subscriptions. Caltrain, the suburban rail line from San Francisco south to Palo Alto and San Jose, provides bike parking at all 32 stations, with a total of 1,100 bike lockers and 400 bike racks.

The San Francisco Bay Area had five of the ten bike stations in the USA in 2009: 226 bike parking spaces at two Caltrain stations and 433 spaces at three BART stations. The BART and SF Caltrain Bike Stations provide free, attended bicycle parking, while the Palo Alto facility is an unattended, fee-based garage. Utilization rates of the bike stations vary widely, from over 100% at the Berkeley BART station to only 11% at the Palo Alto Caltrain station. BART will soon triple the size of the Berkeley bike station and move it above ground to increase accessibility.

Cyclists prefer to take bikes on board, however. A 2008 survey found that 72% of bike-and-ride passengers carried their bikes with them, compared to only 28% who parked them at BART stations. Bikes are allowed on BART trains except during peak hours in the peak direction. Although Caltrain has no time restrictions, cyclists are often denied boarding on rush hour trains because all bike spaces are already occupied. Neither BART nor Caltrain charge a fee for bringing bikes on board. Moreover, Caltrain's lead cars provide special accommodations for 16–32 bikes, depending on time of day and direction of travel. Most of the numerous ferry lines in the Bay Area also permit bikes on board with no extra fee. Folding bikes are allowed on BART and Caltrain at all times, but are not permitted on board San Francisco's MUNI buses, streetcars, cable cars, and light rail vehicles. Complementing bike access to BART and Caltrain services, virtually all buses of all public transport systems in the San Francisco Bay Area are equipped with bike racks, free of charge to cyclists.

There is limited coordination of bike routes with public transport routes. To avoid bus-bike conflicts, bike routes are not usually located on bus routes in San Francisco, but are on parallel streets. Due to the extensive and fine-grained network of bus and rail routes in San Francisco, bike routes often lead to public transport stops, even without any explicit coordination. The Regional Bicycle Plan as well as the Bike Plans of BART and Caltrain explicitly encourage coordination of bike routes and facilities with public transport. Outside of San Francisco, where public transport routes and stations are farther apart, many communities make an explicit effort to coordinate bike routes with key stops.

Overall, bike-transit integration efforts in the San Francisco Bay Area have been successful. The percentage of public transport trips combined with cycling has more than tripled since 1990. Nevertheless, several problems remain. For example, it is difficult for cyclists to get across the San Francisco Bay during rush hours, since bikes are prohibited from BART trains in peak directions and not permitted on the Bay Bridge. Similarly, Caltrain has problems accommodating bikes on board in the peak hour and often denies boarding to cyclists. The exclusion of bikes from Muni's light rail lines is also a problem for cyclists. Overall, however, the available evidence suggests that bike-transit integration efforts have been successful.

Portland

As shown in Fig. 2, Portland has the highest bike share of work trips of any large American city (6.0%). Thus, one would expect a high degree of bike-transit coordination. Bike-and-ride in Portland, however, is quite different from that in San Francisco and mainly involves bikes on transit vehicles. TriMet, Portland's public transport system, estimates that ten times more bikes are taken on their LRT vehicles than parked at LRT stations (2,100 vs. 200 per weekday). There are no fees, no permit requirements, and no time of day or directional restrictions for taking bikes on LRT vehicles. Every train has a low-floor car especially designed to facilitate bike access, with waiting areas and four bike hooks located near the doors. But passengers without bikes have priority to board crowded trains. All buses in the Portland area have bike racks, another inducement for cyclists to ride with their bikes instead of parking them.

By comparison, Portland does not provide much bike parking at train and bus stops. In 2009, there were a total of 670 bike parking spaces at TriMet LRT stops and transit centers (major transfer hubs for several bus or LRT lines). Of those, almost half were bike lockers. In addition, there were city-owned bike lockers at 15 locations in downtown Portland, most of which are near bus or rail services. In sharp contrast to San Francisco, Portland does not have any bike stations, which is surprising given its high bike mode share and wide range of other pro-bike policies and programs. Bicycling planners and public transport officials in Portland plan to improve bike parking at transit stops by installing 196 bike lockers and 168 bike racks at LRT extensions.

Portland cyclists prefer taking their bikes on board transit vehicles. A survey by TriMet indicated that 76% of cyclists would not be willing to park their bikes at a transit stop even if there were sheltered and secure bike parking available. The advantage of taking bikes on buses or rail vehicles is that bikes can then be used at both ends of the transit trip. So the aversion to parking bikes at bus and rail stops may be due more to convenience than to concerns over theft or vandalism.

Portland carefully and explicitly coordinates its bikeway network with its public transport network. The city has set the goal of a seamless link between cycling and transit. Bike routes are designed to facilitate access to public transport stops. Most transit centers are served by multiple bikeways. Moreover, city planners give special consideration to enhancing bike access to transit stops in outlying areas too far away from the city center for most people to cover by bike alone. Nevertheless, as in most cities, there are some public transport stops that are difficult or dangerous to access by bike. As the largest of America's three platinum level Bicycling Friendly Communities, Portland has already made impressive progress at integrating cycling with public transport and seems sure to continue on that path.

Vancouver

Similar to San Francisco and Portland, Vancouver has vigorously promoted the integration of public transport and cycling. The unique advantage in Metro Vancouver is TransLink, the fully integrated, multimodal regional transportation authority. Unlike the other case studies, public transport, major roadways, and bicycling in Vancouver are all handled within the same agency. The coordination of cycling and public transport is obvious and natural in such a multimodal agency – as reflected in TransLink's plans, funding, construction projects, vehicle procurement, and operating procedures. Over the past 10 years, TransLink has spent over $12 million specifically on bike-transit integration.

As in the San Francisco and Portland areas, all buses in Metro Vancouver are equipped with bike racks. Similar to San Francisco's BART, bikes are allowed on Vancouver's SkyTrain except during peak hours in the

peak direction due to problems of overcrowding. Until recently, there were no special accommodations for bikes on SkyTrains, but all future vehicles will provide a special area for bikes in the rear of each car with a leaning rail and fold-up seats. Bikes are allowed at all times on West Coast Express trains for a $.50 charge. SeaBus ferries permit bikes on board at all times without charge. Almost all of TransLink's rail and ferry services are fully accessible – through elevators, ramps, or level boarding – thus facilitating bike-and-ride.

There are bike racks at all SkyTrain and West Coast Express rail stations as well as park-and-ride lots and transit nodes with interchanges of several bus or rail lines. In 2008, Vancouver had a total of 1,060 parking spaces at transit stops: 660 spaces in racks and 400 secure bike lockers. TransLink plans to increase the overall supply of bike parking at transit stops in the coming years, with a special focus on improving the quality of bike parking, especially secure short-term bike parking. Bike stations at the most important transit hubs are also being considered.

Thanks to its multimodal orientation, TransLink explicitly coordinates bike routes with public transport. For example, the construction of the Millennium, Expo, and Canada SkyTrain lines included traffic-protected, parallel bike routes to foster bicyclist access to public transport. Another aspect of TransLink's multimodalism is the focused promotion of cycling in central corridors where bus and rail vehicles are the most crowded, and where cycling has the potential to divert some of the overload and thus reduce crowding. That coordination of demand and supply between the two modes is rare and emphasizes the advantages of multi-modal agencies such as TransLink.

Minneapolis

Although Minneapolis is, by far, the coldest of the eight cities, it has the second highest bike share of work trips after Portland (4.3% vs. 6.0%). Public transport's share of work trips is slightly higher in Minneapolis than in Portland (13.4% vs. 11.2%), but much lower than in any of the other cities (Fig. 2).

Metro Transit had 497 bike parking spaces at its light rail and bus stops in 2007: 271 spaces in bike racks and 226 bike lockers. Minneapolis has a staffed bike station, the Midtown Bike Center, with 100 bike parking spaces, repairs, rentals, and a café. It is only a block from the Chicago and Lake Streets transit hub, which serves two of the city's busiest bus lines. Perhaps the city's most ingenious policy is the official designation of 35,000 traffic sign posts as bike parking with 70,000 bike parking spaces, assuming two bikes parked at each post. The city also considers that a form of bike-transit integration, since many traffic sign posts are near bus stops, including the bus stop post itself.

All Metro Transit and suburban transit buses are equipped with exterior bike racks, and the city has five stationary bike racks for first-time users to practice loading their bikes. Every light rail vehicle has interior vertical racks that accommodate four bikes. Bike-and-ride has become increasingly popular in Minneapolis. Metro Transit surveys in spring 2007 and fall 2008 found a doubling in the number of bicycles transported on bus racks and a 41% increase in bikes on light rail. On an average weekday in 2008 Metro Transit buses carried 870 bikes. Only 4% of cyclists had to wait for another bus due to racks being filled.

There is no explicit policy of coordinating bike routes and transit stops in Minneapolis, and city officials emphasize the need to improve cycling facilities feeding into public transport stops. Some bike routes already lead to transit stops or parallel transit lines. For example, the Hiawatha LRT line runs parallel to an off-street bike path for most of its length in Minneapolis, thus providing an alternative for cyclists on that route.

Chicago

With the second largest transit system in the USA, Chicago has made impressive efforts to integrate cycling with public transport. Its special distinction lies in the innovative provision of bike parking at rail stations, tailoring the design of parking facilities to each station's particular situation. With 6,420 parking spaces at its rail stations, Chicago has about the same amount of bike-and-ride parking as the San Francisco Bay Area, and far more than other cities in North America.

There are 2,153 bike parking spaces at 131 of the 143 CTA subway and elevated rail stations and 4,267 spaces at 50 of the 76 Metra suburban rail stations. Moreover, indoor or sheltered parking is available at 83 CTA stations, more than any other transit system in North

America. The specific location of bike racks inside the stations provides both weather protection and greater security, since they are usually placed within easy sight of station attendants and other passengers. Chicago is currently installing additional sheltered bike parking for 382 bikes at four CTA stations, and the city has funding to install bike shelters for 250 more bikes in 2010.

The largest bike station in the USA is located in Chicago's Millennium Park, immediately above the terminal station for two of Chicago's suburban rail lines. The bike station is easily accessible from downtown Chicago and the 18-mile Lakefront Trail. It provides secure, indoor parking for 300 bikes as well as convenient lockers, showers and towel service, bike rentals, bike repairs, and guided bicycling tours.

The CTA regularly monitors bike parking needs by conducting bi-annual bike rack inventories and measuring usage rates. It then works with Chicago DOT to install additional racks where needed.

As in most of the case study cities, all of Chicago's buses have bike racks – including CTA buses as well as PACE suburban buses. Bikes are permitted on CTA and Metra trains except during weekday rush hours. And just as most of the other cities, no fees or permits are required for the use of bike racks on buses or for bringing bikes on trains.

The biggest challenge to bike-transit integration in Chicago is the difficult access to train platforms. Because most of the rail lines are so old, only 54% of CTA stations and 68% of Metra stations are ADA accessible. Thus, cyclists are often forced to carry their bikes up long flights of stairs. Few stations have elevators, and cyclists are not permitted to use escalators.

Chicago DOT, transit agencies, and the cycling community are aware of these problems and have made improvements in bike-transit integration a top priority. Chicago's Bike Plan 2015 sets goals of further expanding and improving bike parking inside and outside of rail stations, remodeling stations to make them more accessible to bikes, providing more park-and-ride facilities, and establishing a second bike station with better transit connections.

Toronto

The combination of high rates of transit use and rising cycling levels has prompted a range of efforts to integrate the two modes in the Toronto metropolitan area. The main approach has been to provide ample bike parking. With over 15,000 post-and-ring bike racks throughout the city, Toronto has more bike parking than any other city in North America. That includes bike parking at almost all rail stations. In 2008, there were 1,192 short-term spaces in bike racks at Toronto Transit Commission (TTC) subway stations and 579 short-term spaces in racks at GO Transit suburban rail stations.

Yet there is a severe shortage of secure bike parking, with only 114 bike lockers in the entire transit network. Consequently, Toronto plans on greatly expanding the supply of secure parking in 2009 and 2010 through installation of more bike lockers and completion of a new bike station at Union Station, the main transit hub in downtown Toronto, providing bus, streetcar, subway, and suburban rail connections. The bike station will provide secure, sheltered parking for 200 bikes. Construction of an even larger bike station at City Hall is planned to begin in 2010. That facility will be close to several bus and streetcar lines. The GO Transit suburban rail system is improving its bike parking by expanding sheltered parking to all stations by the winter of 2009–2010.

As in most cities with high levels of rail transit use, bikes cannot be taken on TTC subways and streetcars during weekday peak hours. Even when permitted, there are no special provisions for bikes on TTC subway cars. Similarly, bikes are not allowed on any GO Transit trains headed toward Union Station in the morning peak (6:30–9:30) or departing Union Station in the evening peak (3:30–6:30). Folding bikes are permitted on all public transport vehicles at all times. Bike access to rail transit is limited by the lack of elevators in most subway stations. As in Chicago, cyclists in Toronto must carry their bikes up and down long flights of stairs to reach the train platforms. Only 41% of TTC subway stations are wheelchair accessible, while 75% of GO Transit stations are accessible, either through elevators or ramps.

Toronto is making rapid progress equipping its buses with bike racks, which can be used at any time, even during peak periods. In 2008 only 55% of TTC buses had bike racks, but all new buses have racks, and every month about 40 older buses are retrofitted with racks. By the end of 2010, all TTC and GO Transit buses will have bike racks, thus facilitating bike and ride throughout the region.

There is almost no explicit coordination of bike routes with transit routes and station stops. Instead, the guiding principle of bike route planning is to put every Torontonian within a 5-min bike ride of the bikeway network. The many transit stations and fine-grained street network in much of the central city facilitates bike access to TTC stations. In suburban areas, however, many streets are circuitous and do not connect across arterials, making it difficult for cyclists to avoid major arterials while en route to a transit station.

Although bike-transit integration in Toronto faces some serious challenges, much progress is being made, partly thanks to the Province of Ontario's Metrolinx BikeLinx Program, which helps finance bike parking at stations and bike racks on buses. With the two new bike stations, additional bike lockers, expansion of sheltered parking, and completion of bike rack installation on all buses by 2010, Toronto will have made great strides coordinating cycling and public transport.

Washington

Bike-transit integration in Washington is similar to the situation in the San Francisco Bay Area. Both metropolitan areas rely on regional metro systems started in the late 1960s and early 1970s: BART in San Francisco and Metrorail in Washington. There is bike parking at almost all of Washington's 86 Metrorail subway stations, with a total of 1,800 bike racks and 1,300 bike lockers. The parking facilities are popular, with usage rates at most stations ranging from 50% to 100%. In October 2009, a new bike station with spaces for 150 bikes will open next to Union Station, providing convenient connections to Metrorail as well as suburban trains leaving from Union Station. The bike station will also offer bike rentals, repairs, and accessories as well as storage lockers and changing rooms.

In 2008 a new bike sharing program began in Washington, similar in technology to the Velib system in Paris, but on a much smaller scale: only 120 bikes compared to over 20,000 bikes in Paris. It facilitates bike-and-ride because eight of the ten bike sharing docking stations are at Metrorail stops. The short-term rental bikes can be used to get to and from Metrorail stations, thus serving as feeders and distributors for transit.

Bikes are allowed on Metrorail trains except during morning and afternoon rush hours on weekdays: two bikes per car on weekdays, four bikes per car on weekends. Unlike the much older subway systems in New York and Chicago, all 86 Metrorail stations have elevators (271 in total) and are ADA accessible. That facilitates access to platforms for cyclists as well, who are, in fact, required to use the elevators and are not permitted on escalators. In contrast to the Metrorail, VRE and MARC suburban trains do not allow bikes on board at any time unless they are folding bikes. All 1,450 WMATA buses have bike racks, but some buses run by suburban agencies do not.

In theory, bike plans for the Washington area establish the goal of coordinating bike routes with transit routes, but in fact, nothing has really been accomplished in this area except by accident. Overall, however, bike-transit integration in the Washington area is successful. The biggest gap is the exclusion of bikes from the Metrorail system during peak hours. To some extent, this is unavoidable due to the overcrowding of metro cars, just as on the BART, Toronto, and Chicago subway systems. But it reinforces the need to expand bike parking at the many Metrorail stations where current capacity is insufficient.

New York/New Jersey

With 55% of all work trips by public transport, New York City has, by far, the highest transit mode share of any city in North America. Thus, one might expect substantial efforts to coordinate cycling with public transport. In fact, New York City's transit systems have done little to promote bike-transit integration, far less than any other city in this study. The Metropolitan Transportation Authority (MTA) does not provide bike parking of any kind at the city's 467 subway stations, so the only option for cyclists is to park on nearby sidewalks. The MTA's suburban railroads, the Long Island Railroad (LIRR) and Metro-North Railroad (MNR), offer bike parking at some of their stations – but MTA has no information on the total number of spaces (MTA, 2009).

Compounding the problem of insufficient bike parking along the many subway and suburban rail lines of the MTA, there is no secure bike parking at any public transport terminals in Manhattan. Train, bus, and ferry terminals do not even offer short-term

parking in bike racks. Thus, cyclists must seek out the occasional bike rack on sidewalks within a few blocks of the terminals or risk having their bikes confiscated if parked at traffic signposts, which is illegal in New York.

NYC subways are unique in permitting bikes on board trains at all times, but it is difficult to get bikes to the platforms. Only 16% of New York's subway stations are ADA accessible via elevators or ramps. At the remaining 84% of stations, cyclists must carry their bikes up and down long flights of stairs, as they are prohibited from using escalators in stations where they are available. Bikes are allowed on the MTA's two suburban railroads (MNR and LIRR) except during peak hours in the peak direction, but cyclists must register in advance and purchase $5 lifetime permits. Folding bikes are allowed at all times. In 2008, 18% of LIRR stations and 52% of MNR stations were not ADA accessible – considerably less than the 84% inaccessible MTA subway stations, but still a problem for cyclists having to carry their bikes up and down stairs.

Bike-bus integration is almost non-existent in New York City. Not a single bus in the MTA's fleet of 5,929 buses has a bike rack. That contrasts sharply with 100% of buses equipped with bike racks in most of the other case-study cities. Only since spring 2008 have folding bikes been allowed on most MTA buses.

There is no explicit effort to coordinate bike routes with transit routes in New York City. That is not a severe problem in most of the city because the transit network is so dense that most neighborhoods are served by a nearby subway or bus line. In the suburbs and the outermost portions of the city, however, the complete lack of bike-transit route integration is a serious shortcoming. Precisely in those lower density areas where cycling would provide an ideal feeder mode to more distant transit stops, bikeways are almost exclusively recreational paths that do not connect to practical destinations such as transit stations.

Not only does New York compare unfavorably in its bike-transit integration to the seven other case study cities, but it is surpassed by the New Jersey portion of the Greater New York metropolitan area. In 2008, New Jersey Transit (NJT) offered bike parking at 90% of its suburban rail stations and 80% of its light rail stations, with a total of 2,400 spaces, including 376 secure bike lockers. Unlike the MTA in New York, NJT provides bike racks at all three of its major terminals in Hoboken and Newark (Penn Station and Broad Street). Bikes are allowed on all suburban rail and light rail lines except during rush hours in the peak direction, and no permits or fees are required. Folding bikes are allowed on all NJT vehicles at all times. Roughly half of NJT's 2,000 buses are equipped with bike racks, and an additional 200 buses are outfitted with racks each year. By 2014, 95% of NJT's buses will have bike racks. The main problem in New Jersey is the almost complete lack of bike paths and lanes leading to NJT rail stations and bus stops.

Summary of Case Studies

Most of the case study cities have greatly improved the coordination of bicycling and public transport in recent years. They have increased bike parking at transit stops and better accommodated passengers wanting to take their bikes with them on buses and rail vehicles. Only a few transit systems have measured the actual extent of bike and ride, but the available evidence is encouraging. In Washington DC, for example, the number of bicyclists riding on Metrorail increased by 60% between 2002 and 2007. At some stations, cyclists accounted for up to 4% of all passenger boardings. In Minneapolis, Metro Transit carries over 250,000 bicycles annually and reports a doubling of bikes on buses between spring 2007 and fall 2008. Roughly 4% of Portland MAX light rail passengers carry their bikes onto the vehicles with them. In the San Francisco Bay Area, the share of passengers accessing BART stations by bike rose from 2.5% in 1998 to 3.5% in 2008, with an average of 10,920 bike-and-ride trips per day.

As shown in Table 1, there is considerable variation among the eight case studies. The San Francisco Bay Area, for example, provides the full gamut of bike-integration measures and has been at the vanguard of innovations to promote bike-and-ride. By comparison, New York's transit systems have made few provisions to accommodate cyclists, lagging behind the other case study cities in both the quantity and quality of bike-integration measures. All eight of the cities have plans to further improve bike-transit integration. Thus, it seems certain that the promising trends of recent years will continue.

Bicycle Integration with Public Transport. Table 1 Overview of bike-transit integration measures in eight large American and Canadian cities [37–54]

Bike parking at transit stops and stations	Bikes on transit		Bike routes and transit stops	Highlights: strengths and challenges
	Bike racks on buses	Bikes on trains		
San Francisco (population city: 0.8 m, metro: 4.2 m)				
BART provides 4,313 bike parking spaces, including 716 conventional and 294 electronic bike lockers	All buses have bike racks (usage rates vary from 17% to 43%)	BART allows bikes on all non-peak trains and during peak times in non-peak directions. BART expanded on-board space for bikes on select cars	Bike routes often parallel MUNI bus routes and intersect with transit stops. No explicit planning process coordinating transit and cycling routes in SF	Strengths: Racks on all buses; extra space for bikes on Caltrain cars; bike access to BART off-peak; extensive bike parking at BART and Caltrain stations; five bike stations
Caltrain's 32 suburban rail stations offer 400 bike racks and 1,100 bike lockers		Caltrain: special lead cars designated for bike use all day, space for 16–32 bikes	The Regional Bicycle Plan as well as the Bike Plans of BART and Caltrain encourage coordination of bike routes and facilities with public transport	Challenges: No bike access on MUNI light rail; need more dedicated space for bikes on Caltrain; no coordination of bike routes with MUNI routes; no rush hour access for bikes on BART
Five bike stations with 659 bike parking spaces at BART and Caltrain Stations				
Portland (population city: 0.5 m, metro: 2.1 m)				
Bike racks and/or lockers at almost all TriMet LRT stops and transit hubs providing 670 bike parking spaces; including 320 secured spaces	All buses have bike racks	MAX light rail: bikes permitted if space is available on cars, but non-cyclists passengers have priority	Explicit coordination of bike routes with transit stops with the goal of establishing a seamless link between the two modes	Strengths: Racks on all buses; dedicated space on LRT for hanging bikes near doors; free access for bikes 24/7; easy access to low-floor trains
15 downtown locations with bike lockers; usually close to light rail or bus stops				Challenges: Lack of good quality and quantity of parking at most train stations; poor design of access to stations by bike; cyclists are often denied boarding on LRT during peak
Vancouver (population city: 0.6 m, metro: 2.1 m)				
660 bike parking spaces in bike racks at SkyTrain stations and at transit transfer nodes	All buses have bike racks	SkyTrain: bikes allowed anytime except in peak periods in peak direction	Central Valley Greenway and BC Parkway facilitate access to and from transit stations	Strengths: Bike racks on all buses; bikes allowed on SkyTrain except during peak hours in peak direction; integration of bike network and transit stops; bike parking at all major transit stops; 24/7 no cost bike access on SeaBus
400 secure bike lockers at most Sky Train and all West Coast Express stations		SeaBus: bikes allowed at all times	Translink's $2.55 million annual cost sharing of cycling infrastructure favors projects that facilitate access to transit	Challenges: Need more and better bike parking; need more capacity on SkyTrain to accommodate cyclists

Bicycle Integration with Public Transport. Table 1 (Continued)

Bike parking at transit stops and stations	Bikes on transit		Bike routes and transit stops	Highlights: strengths and challenges
	Bike racks on buses	Bikes on trains		
Minneapolis (population city: 0.4 m, metro: 3.2 m)				
271 bike parking spaces and 226 bike lockers next to Metro Transit stops and at park-and-ride lots. Usage rate of 28% of bike parking spaces at Hiawatha LRT line	All buses have bike racks. Bike on bus demonstration racks in various locations	27 light rail vehicles with on-board interior vertical racks that accommodate 4 bikes per vehicle	No explicit coordination of bike routes and transit. But connection to transit lines is a prioritizing criterion for bike projects funded by the MPO	Strengths: Bike racks on buses and trains; bike racks and lockers at most train stations; marketing information on bike transit integration provided by Metro Transit
City bicycle ordinance encourages parking bikes at sign posts, which are within a block of most bus stops. Bike station 1/10 of a mile from the Chicago and Lake Street transit hub			The Hiawatha LRT line parallels an off-street bike path for most of its length in Minneapolis	Challenges: Bike racks needed at four more LRT stations; lack of bike paths and lanes leading to train stations and bus stops
Chicago (population city: 2.7 m, metro: 9.5 m)				
2,153 bike parking spaces at 131 of the 143 CTA stations and 4,267 bike parking spaces at 50 of the 76 METRA suburban rail stations. Most (83) CTA stations provide indoor or sheltered bike parking. Usage rates of 90% and 50% for indoor and outdoor racks	All CTA and PACE buses have bike racks	Bikes permitted on CTA and METRA trains during off-peak. Bikes not permitted on escalators in stations	The routing of on-street bikeways in Chicago takes the location of transit stations into account. CTA system maps show bike parking possibilities at stations	Strengths: Ample bike parking at 131 CTA stations, of which 83 provide indoor parking. State-of-the-art Millennium bike station at downtown terminus of suburban rail line; CTA regularly collects bike rack usage data to add parking where needed
Largest bike station in the USA with indoor parking for 300 bikes, right above the terminal station for two of Chicago's suburban rail lines				Challenges: The CTA subway is old with limited ADA facilities; flights of stairs make it difficult to bring bikes on board
Toronto (population city: 2.5 m, metro: 5.5 m)				
1,771 short-term bike parking spaces and 114 bike lockers at TCC subway and GO Transit stations	55% of TTC buses and all GO Transit buses have bike racks	Bikes permitted on TTC subways, RT trains, streetcars, and buses without bike racks except during peak hours	The guiding principle of bike facility planning is to put every resident with a 5 min bike ride of the bike network	Strengths: Extensive transit system with high mode share; bike racks on most buses; bikes allowed off-peak on streetcars, subways, and suburban rail; bike parking at most transit stops

Bicycle Integration with Public Transport. Table 1 (Continued)

Bike parking at transit stops and stations	Bikes on transit		Bike routes and transit stops	Highlights: strengths and challenges
	Bike racks on buses	Bikes on trains		
New bike station at Union Station (opening spring 2009) with secure, sheltered parking for 200 bikes. Second bike station planned	All TTC buses will be equipped with bike racks by end of 2010	Bikes permitted on GO Transit trains except on trains arriving and departing from Union Station in peak direction	The Waterfront Trail which spans the Greater Toronto Area parallels the busy GO Rail Lakeshore corridor and is in close proximity to many stations	Challenges: No bikes allowed on rail transit during peak hours; lack of elevators in many stations; more bike parking and secure lockers needed at stations; no coordination of bike routes with transit stops
Washington, DC (population city: 0.6 m, metro: 5.3 m)				
1,800 bike racks and 1,300 bike lockers at Metro stations. No bike parking at bus stops, except major transit hubs with rail stations	All WMATA buses have bike racks	Bikes allowed on Metro trains during off-peak. Cyclists must use elevators between the street and the station platforms	Drafting of DC bike plan took the location of metro stops into account, particularly for the bike route network and facility recommendations	Strengths: Bike racks on all buses; bikes on Metro except during peak; lockers and racks at all stations; SmartBike short-term rentals at 8 Metro stations
Bike station for 150 bikes to open in July 2009 at Union Station		Bikes not allowed on MARC trains. VRE allows bicycles on some trains		Challenges: Restricted bike access hours on Metro; bikes restricted on VRE and MARC suburban rail
New York City (population city: 8.2 m, metro: 18.8 m)				
No dedicated bike parking at rail stations or transit terminals. Some bike parking provided by NYCDOT on sidewalks, often near transit stops. No secure bike parking of any kind in NYC	No buses with bike racks in NYC; Roughly half of NJ Transit busses have bike racks in 2010 (planned increase to 95% by 2014)	Bikes permitted on the NYC subway at all times, but only 16% of stations ADA accessible, with elevators or ramps	No explicit coordination; but the transit network in the city is so dense that most of the bike network is close to transit	Strengths: 24/7 bike access and no fees or permits on NYC subway system, most extensive in North America; big increase in bike racks and bike parking on NJ Transit
Bike parking at a third of MTA suburban train stations in NYC; bike lockers at 18 LIRR and 6 MNR stations; bike parking at 90% of NJ Transit train stations and 80% of LRT stations (a total of 2,400 bike parking spaces, with 376 bike lockers)		All suburban trains allow bikes on board during off-peak hours, but limit of 2–4 bikes per car on weekdays; NJ Transit LRT allows bikes on trains during off-peak hours with a maximum of 4–6 bikes	No coordination of bike network with transit stations and routes in suburbs; most suburban cycling facilities are recreational and do not lead to transit stops	Challenges: No bike racks on MTA buses in NYC; limited parking at MTA suburban rail stations and no bike parking at two main train stations in Manhattan; no secure bike parking; difficult to access platforms: only 16% of subway stations with elevator access

Future Directions

North American cities have been making impressive progress integrating cycling with public transport. Since 2000, the percentage of buses with bike racks has almost tripled. Bike-rail integration has also advanced. Most light rail, metro, and suburban rail systems permit bikes on their rail vehicles except during peak hours, and they increasingly provide special accommodations for cyclists such as bike hooks, racks, and rails in special areas of rail cars. Complementing provisions for bikes on transit vehicles, bike parking at transit stops has been vastly expanded over the past 10 years, with large increases in the number of racks as well as improvements in the convenience, security, and shelter of bike parking.

While cycling and public transport have considerable synergies, there are some inevitable conflicts. Surveys in some cities indicated that cyclists prefer to take their bikes with them on rail vehicles so they can use them at both ends of the trip. That can cause problems during peak hours, however, when all available capacity is needed to accommodate passengers, and there is no extra room for bikes. Taking bikes on buses is much less of a problem since bike racks are external and do not reduce passenger-carrying capacity. But even bike racks can be filled to capacity during the peak, forcing cyclists to wait for later buses.

Paradoxically, bike-and-ride can become problematic where it is most successful. Capacity problems are most likely to arise in cities with well-used public transport and high levels of cycling. That is why the European approach to bike-and-ride has favored the provision of ample, sheltered, secure bike parking at transit stops instead of accommodating bikes on transit vehicles. Similarly, in North American cities with overcrowding of rail vehicles during rush hours, the focus should probably be on providing improved bike parking at rail stations. Not only is more parking needed, but it should be of higher quality, with more sheltered and secure spaces. Major transit terminals should include multi-service bike stations, such as those in northern Europe. Similar to the concept of "complete streets," an appropriate goal of transit systems in North America should be to provide "complete stations," which fully accommodate the needs of cyclists. That includes making rail platforms more accessible to cyclists, which would also improve accessibility for persons with disabilities.

Such bike-and-ride provisions cost money, but they are much cheaper than park-and-ride facilities for motorists [15]. Transit systems should shift their focus from park-and-ride to bike-and-ride, which is more cost-effective as well as more environmentally friendly. To encourage that shift, federal, state, and local government agencies should vastly expand funding for further improvements in bike-and-ride measures.

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Bus Rapid Transit and Light Rail Transit Systems: State of Discussion

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Article Outline

Glossary

Bus rapid transit (BRT) An integrated bus-oriented public transport service composed of six basic elements: higher-quality, more styled buses; a well-designed service plan, including route structure is faster and more frequent transit service than typically experienced with regular route local bus service; upgraded, appealing passenger stations; roadway infrastructure that gives BRT priority in mixed traffic or separated from other traffic entirely to help ensure faster travel times; intelligent transportation technologies, not only for traffic priority as mentioned above but also for real-time passenger information and vehicle tracking to ensure more ambitious service schedule; and clear, distinct branding and marketing [1].

Bus rapid transit vehicle A bus used in BRT service, typically with advanced features such as aerodynamic styling, hybrid electric drive or other advanced propulsion, and real-time tracking systems, similar to what are now used in rail transit systems.

Buy America Provisions of federal transit law that govern purchases of goods with federal surface transportation assistance grants. Certain aspects of this policy date back to protectionist sentiments of the 1930s. In 1978, Congress stipulated that for purchases of rolling stock, these would be considered to be US made if they were assembled with at least 60% of components and materials by value supplied by US sources. The rules have been subsequently refined and subject to controversy several times since [3].

Capital assistance/expenditures Government subsidies for expenses related to the purchase of equipment and facilities, such as stations, buses, and trains; maintenance facilities; and support systems. Such equipment typically means property that has a useful life of more than 1 year. Capital expenses do not include operating expenses that are eligible to use capital funds.

Commuter rail service Regional-distance, usually locomotive-hauled passenger train service often sharing tracks with freight railroads. Chicago's Metra service is an example.

Federal Transit Administration A sub-cabinet-level government agency of the US Department of Transportation that administers a variety of grant programs that help fund bus and rail transit projects in US cities, Puerto Rico, and the US territories, as well as rural areas and federal lands.

Fixed-route bus service Traditional form of transit bus service, typically with frequent stops along a defined route. The bus services of the Chicago Transit Authority are an example.

Light rail transit (LRT) A form of urban rail public transportation that generally has a lower capacity and lower speed than metro (also known as heavy rail) systems, but higher capacity and higher speed than traditional streetcar systems. These rail systems are typically electrically powered, usually by overhead catenary. They ideally operate their own rights-of-way separated from other traffic but if necessary can also operate in mixed traffic on city streets [2].

Modal split Term of art in public transportation for market share. That is, the percentage of journeys taken with the various forms of public transportation, as compared with walking, bicycling, or the private automobile.

Operating assistance/expenditures Government subsidies for expenses associated with the operation of the transit agency and its passenger services, including vehicle operations (e.g., bus, train, "dial-a-ride," and vanpool services), vehicle and facility maintenance, and general administration (e.g., marketing,

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top management, insurance, and finance). Operating expenses also include salaries, wages, and benefits as well as outsourced services under contract.

Privatization In its strictest definition, it is the return of publicly owned and operated public transport services to the private sector. However, in the USA, it is also defined as the contracting of publicly owned services to private companies, private participation in the capitalization or ownership of these publicly owned services, or the franchising of these services to private firms.

Public transport service Bus and rail services operated either by public or private organizations on a scheduled or on-demand basis. These services are distinct from charters, which are hired for groups such as tours.

Public–private partnerships/models Synonymous with most definitions of privatization except the complete return of transit services to private ownership and operation with minimal oversight.

Purchased transportation services Bus and train service provided by others through a contract; also called contract service.

Rolling stock Industry term for buses and trains and other vehicles used in public transport service.

Transit-oriented development Land use patterns such as higher densities around BRT and rail stations that also contribute to greater transit usage on these systems.

Transportation Equity Act for the 21st Century Also known as TEA 21, the landmark surface transportation assistance law passed in 1998 that ended operating assistance for agencies that served urbanized regions with fewer than 200,000 residents. It also for the first time guaranteed a stream of funding for capital assistance over the 6-year period in which the law was effective, which helped public transportation agencies better manage and plan their capital expenditures.

Travel time savings Industry term for the average estimated savings per trip on new transit systems as compared with the average travel time from a commute taken by an automobile or by the previous bus network serving the route.

Urban Mass Transportation Act The 1964 federal law that began the federal government's involvement in the oversight and financial assistance of regional, state, and local public transport services.

Vehicle maintenance Activities associated with bus, railcar, and support vehicle (e.g., fueling and repair trucks) maintenance (repairs and routine replacement of parts) and servicing (cleaning, fueling, etc.), also including inspection and oversight of these activities. In addition, vehicle maintenance includes repairs due to vandalism and accidents.

Vehicle operations Those activities associated with providing scheduled and on-demand passenger services, such as vehicle dispatching and scheduling, driver and technician training, ticketing and fare collection management, and system security.

Definition of the Subject and Its Importance

Increasingly, light rail transit (LRT) and bus rapid transit (BRT) are the two solutions cities throughout the world most often turn to in a broad variety of urban public transport applications to address a wide range of mobility challenges. While regional rail schemes (also called commuter rail in the USA and Canada) are also experiencing rapid growth, and many cities that have metros (also known as heavy rail in the USA and Canada) continue to expand their networks, LRT and BRT are even faster growing modes.

Whether LRT, BRT, metros, or commuter railroads, virtually all large cities in the developed world now boast at the very least starter urban passenger rail systems, in many instances restoring only partly the networks these cities had a century or more ago. Many of these have since supplemented the initial segments with a second wave of lines to build out their networks. Meanwhile, a growing number of midsize cities in the developed world, including a rapidly growing list of cities in developing countries, have also added networks. Call these stages the first two waves of the worldwide public transport renaissance. Now public transport infrastructure investment is entering a third wave of the renaissance, in which the growth of public transport investment becomes an essential and integral part of a nation's or a region's balanced transport strategy.

BRT is perhaps the fastest growing public transport mode in a century. Only 12 years ago, 17 US cities were selected by the then Federal Transit Administrator Gordon Linton to participate in his BRT Consortium. Just 5 years later, according to congressional sources,

more than 50 and as many as 75 communities have a BRT project in some stage of development. Today, virtually every project seeking federal financial support, regardless of mode, also studies a BRT alternative, thus putting the mode on equal policy consideration with other public transport strategies.

The simplest and most often used definition of BRT is a public transport concept that "thinks like rail but uses buses." The interest in it is borne out of desire to offer increasingly congested cities a flexible, relatively inexpensive alternative to more highways or more expensive and longer-to-implement transit alternatives. Applications range from feeder systems to rail lines (e.g., Los Angeles) to downtown circulators (e.g., Orlando and Denver) to urban transport spines in their own right that can change the region's modal split and stimulate transit-oriented investment (e.g., Bogotá, Curitiba and Eugene, Oregon).

Similarly, applications of LRT range from spines for smaller cities that cannot justify the expense of metro systems to feeder systems to metros or regional passenger railways to circulators that often run in the street with other traffic. These last systems are often called trams or streetcars, as well. The flexibility of LRT also results in systems that operate in their own rights-of-way either underground, in elevated structures or at grade, as well as combinations of all of the above.

Since 1975, 23 cities in North America alone have fueled the rebirth of LRT development. Prior to that year, only seven cities had such services, as most were discontinued in favor of road and highway investments. LRT services now operate in 24 US cities, as well as three each in Canada and Mexico. Still more are under construction or in various other stages of development [4].

Introduction

BRT and LRT systems are being planned, constructed, and opened for service at a faster pace than previously, because these projects today tend to be smaller projects than metros, and as such are better suited for smaller applications, such as network spines for small cities, lines for suburb-to-suburb commutes – long the overwhelming share of journeys to work in the USA and a growing trend elsewhere as well – and for smaller-scale feeders to previously established systems.

In addition, these systems, particularly smaller, often street-running LRT lines known as trams or streetcars, but also BRT in a growing number of instances as well, serve as outstanding reshapers of the built environment and as economic catalysts.

They also help provide solutions to another worldwide trend: the aging of the population in the developed world. It has already taken hold in Japan, Europe, and Canada, and is becoming an increasing challenge of the USA. Older persons generally prefer to drive less, and they require smaller homes. Many also prefer to live nearer to better health-care services, nearer educational, cultural, and arts institutions, and otherwise "where the action is," or where their extended families are – that is, in cities.

This third wave is also driven by other powerful demographic forces. These include the population growth worldwide, as well as the concentration of that population in cities. This urbanization includes not simply the teeming populations of the developing nations, but also in the USA and other developed economies.

As a consequence, this current wave of public transport investment could be the largest expansion yet. However, as will be explained below, this third wave will require a different approach to project development and management.

BRT Developments

There are two major reasons why BRT has been so attractive to city planners. First, BRT projects are typically a fourth of the cost of comparable light rail projects. In addition, BRT can be implemented in roughly a third of the time – or even less – to design and build [5].

For example, the Los Angeles County Metropolitan Transportation Authority (MTA) built and opened its Orange Line BRT in the West San Fernando Valley to light rail standards (to enable a future conversion if it so chose) for $330 million; it took 3 years to design and construct, even with court-ordered stoppages to address neighborhood lawsuits that were concerned about noise, as well as delays caused by construction interruptions from one of the rainiest winters on record in the region. A roughly comparable LRT line in the service area, the Gold Line, took more than

a decade to develop and opened at a cost of approximately $1 billion. Moreover, the Orange Line carries more weekday passengers than the Gold Line [6].

According to the US Senate's Banking Committee staff analyses, more than 50 American communities are developing BRT projects; that number grew with the addition of roughly 2 dozen BRT earmarks in SAFETEA-LU. The accompanying table provides a list of these projects.

Based on a BRT market study performed for the FTA in fall 2002 and updated in 2007 by the advanced transportation research consortium WestStart – CALSTART (Pasadena, CA), as many as five new BRT systems per year and/or ten new BRT corridors could open each year between 2007 and 2010 [7].

Interest in BRT outside the USA is even stronger. Based on success of the TransMilenio, which carries nearly two million boardings per weekday in Bogotá, the government of Colombia has launched a new policy to develop BRT in six other cities. Nearby Ecuador is also planning BRT lines in at least three of its cities. Cities in Peru and Chile are also planning systems.

These successes in many ways emulate the achievements of Curitiba, Brazil, which many point to where BRT began. Despite having the second highest automobile ownership rates in Brazil (only after the country's capital, Brasilia), approximately 70% of weekday journeys are on public transport, mostly on the city's BRT network.

In Asia, Beijing is in the throes of building a six-line network, which began as part of its preparations for the 2008 Summer Olympics; as many as a hundred more cities in China are studying networks, as the government there has included BRT as a transport solution for corridor applications whose volumes warrant less than a tram or light rail investment. The Korean Ministry of Transport is not only involved in assisting several cities in network planning and construction, it is working with a manufacturing consortium to design and commercialize a next-generation BRT vehicle.

Several African cities view BRT as a cost-effective mobility solution in their plans to cope with rapid population growth, most of which is urbanization. Accra, Ghana as well as Johannesburg and Cape Town in South Africa have opened new systems (the latter two in preparation for hosting the FIFA World Cup this past summer).

India's Ministry of Urban Development has issued a new report, "National Urban Transport Policy," which encourages its lower-density cities to develop BRT. Accordingly, the ministry has approved BRT projects in Ahmedabad, Indore, Jaipur, and Pune.

Like South America, Europe and Australia were at the forefront of BRT and continue to witness new projects. In the UK, projects are part of Quality Bus Corridor projects, many of which featuring guided bus systems, including two in Leeds, and one each in Edinburgh, Ipswich, and Bradford. The next to open will be the world's longest guided busway, the 26-km Cambridgeshire Guided Busway built on an abandoned railway right-of-way between Cambridge and St. Ives. Manchester and Luton have also schemes in development.

The industry publication METRO has been tracking the growth of BRT in its annual "BRT 25" survey. Its most recent survey [8] found that the average project cost for BRT networks under development is $143.8 million for new projects.

Light Rail Developments

Though not as fast as BRT in recent years, growth in LRT systems around the world has also been impressive. In the USA, only 11 cities operated modern LRT or their historic counterparts, streetcar services. Today, more than 30 do, and many of those have opened additional lines to build out their networks [9].

In other North American and South American countries, the growth rate has not been as high as in the USA, but most either continue to operate the networks they started or have expanded them. In Mexico, LRT is available in Guadalajara, Monterrey, and Mexico City. In Canada, five cities operate such systems, including Toronto, Edmonton, Calgary, Ottawa, and Vancouver. A sixth, Waterloo, Ontario, is planning such a system.

A recent phenomenon has been the growth in planning, constructing, and opening streetcar lines (also called trams in Europe and some parts of Asia). Interest in streetcars represents a return to an old idea, mainly because of their history in attracting and focusing strong economic development adjacent to their lines. Indeed, the Smithsonian Institution's recent exhibit on public transport history explained that interurban

streetcar lines were built throughout the USA to connect new real estate developments [10]. Henry Huntington became rich not just because of his Pacific Electric rail empire in Southern California but also because of similar, though smaller, enterprises in other parts of the nation [11].

Today's applications comprise either modern technology, such as the systems recently opened in Portland, Oregon, Seattle and Tacoma, Washington, and Nottingham, England, or the one opened in the early 1990s in Strasbourg, France; or heritage (or vintage) systems, such as the one in Kenosha, WI. However, most streetcar lines in the USA and elsewhere in the world employ modern vehicles and other technologies.

Interest in these two modes in recent years has been more intense than that surrounding light rail in the late 1970s and early 1980s and commuter rail in the 1990s, the last emerging markets in public transport. In fact, BRT and streetcars very likely will exceed the other US rapid transit markets not only in project cost but also in the number of projects, even at a time when these other public transport modes are also growing robustly.

In most of the developing nations, BRT will likely be the favored mode, while in many European nations light rail-based systems will be favored. Rail will also continue to be preferred in more densely populated cities of Japan, Korea, and China, though in these countries the mode of choice will just as likely be metro systems as LRT, particularly for the "backbone" lines of networks. However, BRT and tram systems will increasingly become surface network supplements even in these cities, creating stronger networks than benefit all modes of public transport – what telecoms and IT experts call "network effects."

This trend will continue if not accelerate for four fundamental reasons. First, throughout the world, there is a growing recognition that greater investment in public transport improvements is needed to cope with worsening congestion and increasing urbanization throughout the world. Shanghai, Bangkok, Abidjan, Sao Paulo, Mexico City, Cairo, and even Paris and London face ever-increasing metropolitan growth and its attendant problems. Indeed, a recent study found that every other person on the globe lives in a city and that by 2030 60% of the population will live in cities, 23 of them with more than 10 million in population [12]. Only a handful could be characterized as high density.

Second, BRT and streetcars are now considered legitimate tools in urban transport planners' toolkit. Third, BRT, but particularly rail-based public transport modes, are increasingly viewed as good catalysts for economic development, which can also attract private capital to build and operate these systems. Finally, growing fiscal pressures make smaller-scale and faster-to-implement projects more viable relative to more expensive and longer-to-deploy alternatives.

Each of these modes shares some characteristics, but each also has strengths and weaknesses relative to the other modes. For example, BRT is more flexible and typically faster-to-implement, more scalable, and less risky from a project management perspective. On the other hand, streetcars can attract private capital more easily, because their return on investment tends to be much higher – as much as 2–3 times higher – than BRT.

Current and Future Trends

Both rail-based and road-based public transport investments present a much different set of opportunities for policy-makers and thus will continue to require different strategies. These are briefly summarized below and elaborated upon later:

First, BRT and LRT projects in the future will tend to be smaller but many more will be developed. Each project will be smaller than the transit projects in the past, but there will be many more such investments than traditional, larger rail projects, even though all public transportation investments continue to grow rapidly. Implementation and management of these requires a more nimble and flexible oversight, one that is able to respond to changing conditions more quickly.

Second, such smaller systems will be implemented with much more interdisciplinary interaction not only within the project team but also with some different stakeholders. Often because they are far more likely to be built in smaller cities that have less technical expertise than their larger counterparts, BRT and streetcar systems will be implemented for project sponsors that will tend to rely more heavily on turnkey and concession-based project delivery methods, such as

design-build, design-build-operate-maintain, and build-operate-transfer techniques to transfer project risk to private sector experts, accelerate or even help finance projects than with larger urban rail transport projects. This will require project sponsors and their contractors and other consultants, as well as city officials, professional planners, the business community, and other project stakeholders to analyze opportunities in a more interdisciplinary, collaborative approach.

Third, smaller projects will shift financing of them away from central government funding to more decentralized sources, including state, regional, and local governments and, increasingly, even private sources. The progress of this trend will depend on how each country's government is structured. In the USA, even though federal public transport assistance programs have recently been modified to better assist BRT and streetcar projects, they will likely rely less on federal support and more on state, local, or even private sources of funding, which will require different project management, outreach, government affairs, and financial planning strategies than larger projects. This is partly because the explosive growth in interest in such projects has already outstripped available funding. This resource competition combined with lower-average project costs and faster implementation for BRT and streetcars prompts many localities to bypass centralized funding and approval processes altogether.

In many countries, this is already the norm. For example, the central governments of Germany and France contribute well less than 50% of project cost. Moreover, private concessions are responsible for designing, constructing, and operating most new urban transport projects outside the USA [13].

Meanwhile, another interesting trend that has emerged has been the consideration of BRT designs that can be converted at a future date to LRT. Although many cities have designed busways and bus rapid transit running ways that can be converted to future light rail operation, few cities have done so. Seattle's Downtown Transit Tunnel is the most recent such example.

Several cities, however, are beginning to look at BRT as an incremental step to future LRT, whether as political cover against criticism of rail advocates who see BRT as a lower quality investment or as a way to lay groundwork for an incremental strategy, when ridership and political support warranted a higher-capacity solution.

Various scenarios for designing BRT running ways to accommodate future light rail have been advocated and studied. An interesting recent experience occurred in San Francisco, where city planners there examined how its Geary Avenue Corridor BRT Project could be designed to accommodate light rail transit (LRT) at some point in the future. San Francisco County's Proposition K specifically envisioned that Geary, one of the busiest corridors in the city, accommodate a "BRT service with exclusive lanes and dedicated stations... designed and built to rail-ready standards." The San Francisco County Transportation Authority (SFCTA) staff concluded earlier that light rail was not financially possible within the provisions of the referendum's 30-year Expenditure Plan and thus drafted the plan in a way that required all center-running BRT design alternatives for Geary to be "rail-ready" [14].

Two center-running alignments with exclusive lanes were selected for detailed "rail-readiness" evaluation using three definitions of rail readiness. The first definition is a minimal package of design guidelines that would produce an alignment that does not preclude a future conversion to light rail; such an approach would use LRT-standard horizontal and vertical clearances, grades, adjacent tangents, and turning radii, as well as stations sited at locations that can accommodate a light rail platform (typically 180 ft vs. a typical 120 ft BRT platform).

The second definition goes well beyond this approach, to comprise a series of investments that would lead to LRT conversion much more quickly, with less incremental financial expenditure and fewer impacts to nearby businesses and transit riders. This definition includes the design criteria of the first definition, but would also provide additional design detail for surface and subsurface infrastructure, including all trackwork (rail, fasteners, and concrete supportive slab); all electrical and communications ductbanks, manholes, catenary pole and substation foundations for traction power cables and train control wiring; ductbanks and concrete boxes for stray-current protection against corrosion; any necessary drainage work; and utilities relocation needed, including work to preserve access by these utilities so as not to interrupt BRT service. This definition considerably narrows the

differences between this version of BRT and the cost and construction considerations for light rail. The third definition used in San Francisco is between these extremes in the range of investments, though closer to the first definition.

Because of budget constraints as well as the fact that light rail for this corridor was not likely in the near future or even two decades after revenue opening of BRT, the first definition of rail readiness was selected by city planners. They were concerned that even though the other definitions' additional up-front investment obviated some construction when any decision was made to convert to LRT, the remaining construction needed for LRT would still require a great deal of development time as well as create disruptions to neighborhood businesses and residences [15].

This analysis comports with the experiences of other cities seeking to design BRT running ways for a future LRT. For example, the staff of the Metropolitan Transit Authority of Harris County, Texas (known locally as Houston Metro) returned to a policy that committed to LRT for all five of its future rapid transit lines, after it initially considered "rail-ready" BRT (which was even given a new term, "guided rapid transit") on four of these five lines under development.

Houston Metro staff had repeatedly made representations to the public that the lines can be converted without disruption to service, to include the rail embedded into the corridor and all systems except for the electric traction system [16]. In the end, however, it abandoned any "rail-readiness" strategy and opted to eliminate the incremental step [17].

The difficulties of designing BRT for a future LRT are underscored by the initial design of Seattle's Downtown Transit Tunnel. It was designed to accommodate LRT at some point in the future, and even included rails embedded in the tunnel's roadway. Other important rail transit design elements were incorporated at that time, including rail-oriented horizontal and vertical geometry requirements, tunnel clearances for LRVs, station platform lengths to accommodate four-car LRV trains, station widths, and sizing of structural elements to support LRV loads.

However, LRT technology has changed significantly since the original tunnel's design in the late 1980s, in many ways which were not anticipated when the tunnel was designed roughly two decades ago. For example, the conversion, which was completed in late summer 2007, included a new LRT traction power system (with attendant retrofit of grounding and other corrosion protection), track and platform modifications to accommodate low-floor LRVs not available in North America at the time the tunnel was designed, upgraded fire/life safety systems to comply with toughened regulations, and improved train control and communications systems to support an integrated joint bus and rail operation. Importantly, the tunnel bed was also lowered to accommodate both low-floor LRVs and buses [18].

In addition, the bus service that used the DSTT was rerouted to the surface streets of the area during tunnel reconstruction. To minimize these adverse impacts, additional police officers were assigned at key intersections who supplement the police force that was also reassigned to surface bus operations. A large public information campaign was also launched to explain the transition. The cost of these measures combined with the retrofit work exceeded $100 million [19].

In all three scenarios of rail readiness studied in San Francisco, the most minimal "does not preclude LRT" approach would have cost $2.8 million more than the baseline cost estimate for a two-lane BRT center-running exclusive running way, or slightly less than a 3% premium. For the second scenario, total project costs would have approached nearly 100% more than a comparable baseline center-running BRT running way cost estimate. The third scenario of rail convertibility studied for the Geary Corridor, which includes more features than the first definition but not as many as the second, would have been approximately 10% more than the baseline design [20].

Importantly, some significant costs are excluded from these comparisons, however. For example, vehicles, commissioning and testing costs, and any necessary retrofit of maintenance facilities to accommodate future LRV designs, catenary and substation technologies are not included, because these technologies have been undergoing the most rapid evolution and are thus more difficult to project in the future [20].

Conclusion

When modern light rail systems were developed, the mode represented the avant-garde of the public

transport renaissance, as a growing number of cities throughout the world planned and constructed LRT systems. That wave of the renaissance gave way to subsequent, more rapidly accelerating phases involving BRT and streetcars, as cities increasingly looked upon public transport and strategies that were central to addressing urbanization, congestion, sustainable mobility, and economic revitalization. Because those challenges will be no less daunting tomorrow, the public transport renaissance, particularly the part that includes BRT and street-running light rail, continues to be bright.

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Bus Rapid Transit, Institutional Issues Related to Implementation

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Article Outline

Glossary

Dual-mode buses Buses that operate under both manual and partially-to-fully automated control.

Intelligent transportation systems A system or service designed to make the movement of people or goods more efficient, safer, more economical, and less polluting. Such systems work by applying advanced and emerging technologies in information processing, communications, and electronics to surface transportation needs. People can use these systems or experience their influence at home, at work, driving in his/her automobile, waiting at a bus stop, crossing a street, riding on a bus, or looking for a parking space. Examples of ITS technologies with transit applicability either already deployed in particular settings or at least under investigation, include advanced vehicle identification systems, electronic fare payment systems, interactive trip planning systems (kiosk, personal computer), transit signal priority systems, safety and security systems, intelligent vehicle systems (e.g., collision warning systems (frontal, side, and rear), precision docking, and lane-keeping assistance systems) and operations management systems (e.g., computer-aided dispatch system, automatic vehicle location systems, automated scheduling and dispatch software, automatic passenger counter systems, and vehicle component monitoring systems).

Multimodal Involves more than one mode of transport for passengers.

Quality of service The overall measured or perceived performance of transit service from the passenger's point of view.

Stakeholders A person, group, or organization that has direct or indirect stake in an organization or enterprise because it can affect or be affected by that organization's or enterprise's actions, objectives, and policies. Key stakeholders in the implementation of a bus rapid transit system include public transit agencies and municipal or state departments of transportation.

Technology push/market pull A term customarily used in a company's business strategy for a new product or innovation that implies that a new invention is pushed through research and development (R&D), production, and sales functions onto the market without proper consideration of whether or not it satisfies a user need. On the contrary, an innovation based upon market pull has been developed by the R&D function in response to an identified market need.

Transit choice riders Riders who choose to use transit for their trip making, particularly during peak travel time periods for work-related trips, even though they have other means of travel, especially a motor vehicle, available to them. Such riders may choose transit over other modes for a variety of reasons, including saving money, avoiding driving in congested traffic, being able to use travel time productively for other activities, and helping the environment.

Transit-oriented development (TOD) A mixed-use residential or commercial area designed to maximize access to public transport and often integrates features to encourage transit ridership.

Definition of the Subject

Bus rapid transit (BRT) is an innovative, high-capacity, lower-cost public transit travel mode that can improve urban mobility to help make bus transit more attractive

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by enhancing customer quality of service with an ultimate goal of increasing ridership that contributes to relieving traffic congestion. BRT systems can easily be customized to community needs and incorporate state-of-the-art, low-cost technologies as part of their flexible and incremental implementation approach.

For purposes of this entry, the following definition of bus rapid transit taken directly from [1, 2] is used:

- Bus rapid transit is a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways, and intelligent transportation systems into a fully integrated system with a strong image and identity. Bus rapid transit applications are designed to be appropriate to the market they serve and their physical surroundings, and they can be incrementally implemented in a variety of environments (from rights-of-way totally dedicated to transit to streets and highways where transit is mixed with traffic).

Running ways for BRT include mixed traffic lanes, curbside bus lanes, and median busways on city streets; reserved lanes on freeways; and bus-only roadways, tunnels, and bridges. Most stations are located curbside or on the outside of bus-only roadways and arterial median busways. Similarly, BRT stations have low platforms since many are already being served or are planning to be served by low-floor buses. Conventional standard and articulated diesel or compressed natural gas buses are in wide use for BRT operations, and there is a continuing trend toward innovations in vehicle design, including environmentally clean or green vehicles; dual-mode operations in particularly appropriate settings such as tunnels; low-floor buses; more and wider doors; and use of distinctively branded bus rapid transit vehicles and stations. Service innovations include fare-collection procedures and station design. Intelligent transportation systems range from existing and more customary automatic vehicle locations systems, transit signal priority systems, and passenger information systems to more advanced systems including intelligent vehicle systems.

Introduction

Though there has been renewed interest in its use, bus rapid transit is not a new concept. A brief discussion of the beginnings of bus rapid transit is presented in this section of the entry to provide an historical context of BRT to better appreciate from where their institutional issues derive (section "Institutional Issues: A Broad Perspective").

The Origins of the Bus Rapid Transit Concept

As early as the 1930s in the USA, bus rapid transit was suggested in a transportation plan for Chicago, Illinois, that called for converting rail rapid transit lines to express bus operation on certain highways with on-street distribution in the central business district (CBD) [1]. In the late 1950s, transportation agencies looked for ways to implement high-quality, low-cost transit service; for example, in a 1957 study [3], California investigated high-speed bus operations for commuter travel in the San Francisco Bay Area. The proposal called for using a freeway – then under construction – for high-speed bus service utilizing what was then considered modern improvements including park-and-ride lots, pedestrian friendly designs, and improved amenities. The report acknowledged that BRT was the "most economic form of rapid transit that can be operated in this area under present conditions" [3].

Design studies for bus rapid transit within freeway medians were developed in the late 1950s in the Washington D.C. area, which recommended that "in planning of future radial freeways a cross section . . . be provided to afford maximum flexibility and reserve capacity for vehicles as well as for the mass movement of people" [1]. In 1959, the St. Louis, Missouri transportation plan included an 86-mile bus rapid transit system, of which 42 miles were to be special grade-separated bus roadways. The focus of this proposal was an elevated loop road circling downtown St. Louis [1].

In 1963, Crain [4] presented a BRT concept, calling for transportation planners to devise new transit services that replicate the high performance, door-to-door service offered by automobiles, while remaining within the economic reach of most cities. Such a system, Crain states, "combine(s) the best features of rail rapid transit and conventional bus operations by retaining the flexibility of one while obtaining some of the speed and capacity of the other" [4]. Crain also described the use of exclusive lane use and preferential traffic controls for the rapid bus concept. People-throughput capacity of such a

service was also emphasized in order that this concept be effectively sold to politicians and the public [4].

Crain promoted most of the features that are being incorporated into today's BRT systems including exclusive lanes, transit signal priority, rapid fare-collection techniques, quick boarding and alighting, and enclosed pre-boarding payment stations. His preliminary cost estimates showed BRT producing high-capacity service (10,000–20,000 passengers per hour) at a fraction of the cost of rail. His estimates also showed that BRT would cost only 2% of the cost of rail for at-grade BRT service and only 10% the cost of rail for an elevated BRT system [5]. He also discussed the importance of providing up-to-the-minute schedule information to passengers (a precursor to today's automated vehicle location systems and passenger information systems technologies), the importance of overcoming the negative sentiments of transit (bolstering its image), and the need to properly sell the service (marketing). All of these concepts have been incorporated into what we today know as bus rapid transit.

In 1970, Milwaukee, Wisconsin, proposed a transitway plan that included 107 miles of express bus routes over the freeway system and an 8-mile, east–west transitway equipped with 39 stations (excluding downtown) and 33,000 parking spaces [6].

Dual-Mode Systems

Several additional reports from the 1960s outlined many of the same goals and operational characteristics sought in today's BRT but envisioned an even more sophisticated system. Many of the BRT concepts that were explored during the late 1960s and early 1970s focused on providing BRT with, at least, partial system automation. The most common concept involved the use of dual-mode buses. The idea was to combine the flexible collection and distribution capabilities of a bus system with the high line haul performance of an exclusive right-of-way rail system, all with a single seat trip and utilizing automation technologies. The most emphasized features of the systems during this period tended to be full bus automation (for a portion of the route) and exclusive right-of-way of the line haul segment. The hope was that this automation component would permit a reduction in operating costs by eliminating the need for a driver for a portion of the trip, while providing greater line haul capacity than could be achieved through manual driving alone. Meanwhile, exclusive right-of-way (busway or bus lane) would remove the vehicle from the most heavily congested portions of the trip, and permit higher operating speeds, making the transit trip more attractive. Interest in the dual-mode concept at the time declined due to (1) insufficient technological capabilities for cost-effective automation of vehicles, (2) operational savings based on the assumption that the vehicle would be "driverless" for the trip's line haul portion was problematic, and (3) costs of grade separations envisioned for busways greatly reduced the capital-cost savings as compared to a rail system [6].

Early Busways

During the 1960s and early 1970s, bus rapid transit projects were implemented in several regions within the USA, though appeared to be diluted versions of Crain's original concept. Most bus services that were implemented utilized exclusive bus lanes on freeways, but none really utilized a mix of multiple strategies. These projects, therefore, functioned merely as express bus services, whose effectiveness depended primarily on congestion free bus lanes to provide most of the operational improvements. The most notable projects during this period were the (1) Shirley Busway in Washington D.C. [7, 8], (2) El Monte Busway in Los Angeles, California, (3) Holland Tunnel bus lanes in New Jersey and New York, and (4) bus lanes on various bridges in the San Francisco Bay Area. Most of these facilities were eventually converted into high occupancy vehicle (HOV) facilities to improve their utilization. Primary factors that contributed to these systems not utilizing the entire BRT toolbox of strategies include (1) insufficiently developed or cost-effective technologies and (2) lack of political will to champion their use. Domestically, during the following two decades interest in BRT generally waned as the US transit industry's mode of choice for high traffic corridors tended toward rail-based projects [6].

International Experience

During the 1960s, Curitiba, Brazil, experienced rapid population growth of approximately 3% per year due

to large in-migration from rural surroundings resulting in overwhelming traffic congestion. A 1965 regional plan called for the establishment of developmental policies for transportation whose goal was to encourage growth patterns that would be sustainable and supportive of a viable public transit system. The plan called for a monocentric city with four radial corridors that would bear most of the burden of growth and development in the region. Lacking adequate financial resources for a rapid rail "Metro" system, an approach taken by many of its larger neighboring Latin cities, Curitiba opted for a Bus rapid transit system. Whereas, an underground Metro was priced at approximately \$60–\$70 million dollars per kilometer (\$97–\$113 million dollars per mile) (*1,965 \$US*), the express bus roadways were only \$200,000 per kilometer (\$323,000 per mile) [9–11].

The busway opened for service in 1972, and incorporated many, if not most, of the features outlined in Crain's paper [4, 5]. The system relied on features such as a high or raised boarding platform to match the vehicle floor height [12], pre-boarding fare payment, signal priority, onboard automated announcement systems [12] and high-frequency service to ensure high-quality Metro-like service. Over the last 30 years, Curitiba has been able to incrementally expand and upgrade the system as funding allowed and demand warranted. Instituting strong land use controls, the government has also been able to effectively guide growth to encourage development patterns along structural axes that reinforce and encourage use of the bus system. This has kept Curitiba's central city both a vibrant and a pleasant urban environment.

With the success in Curitiba, several other developing Latin American cities such as Sao Paulo, Brazil, Porto Alegre, Brazil, and Quito, Ecuador, have since implemented systems based on the Curitiba public transit model.

Similarly, Ottawa, Canada also turned to the Bus rapid transit concept when it decided to upgrade its transit system. Ottawa made the decision to use the bus as the backbone of the city's transit system, and started its "Transitway" in 1973 with approximately 6.8 miles of bus lanes. By 1983, the first of several busways were opened providing buses with exclusive, grade-separated right-of-way. By 2000, the system utilized 16 miles of exclusive right-of-way, approximately 7.8 miles of priority lanes, and 2 miles in mixed traffic with nearly 200,000 trips per day capable of carrying 10,000 riders per hour in each direction [6, 13].

The Transitway has features that make it special. In the outlying areas away from the urban core, the Transitway's right-of-way is an exclusive bus lane that is at- and above-grade depending on location usually with one lane per direction. At each station, the right-of-way expands to two lanes per direction to allow for buses to stop without blocking other buses. Moreover, at some locations, the exclusive right-of-way is directionally separated by barrier or a grassy median. In a few locations, the bus uses the freeway for short distances (1–2 miles) in an exclusive bus lane. This lane is the freeway's right-most lane that is an exit-only lane for use only by Transitway buses. It is separated by means of a virtual barrier with diamond symbols painted on the bus lane. Some of the Transitway's stations have similarities to rapid rail stations, not in the sense that they are underground (in fact, there is only one tunnel station on the Transitway's route), but that they are infrastructurally extensive. For example, some of these stations are adjacent to commercial office development and are linked together via enclosed walkway bridges. At one location, the Transitway has a stop immediately outside a major department store that is part of a suburban mall. The extensively built stations are fully enclosed to accommodate Ottawa's winter weather with multiple stops for entry onto and exit from buses. Also, bus routes for non-Transitway lines converge at several of the Transitway's stations. In addition to the Transitway's connection with Ottawa's International Airport, it also connects with Ottawa's central train station via an enclosed walkway bridge linking the two stations [6].

Ottawa is typically heralded as another shining success story for bus rapid transit and several other Canadian cities have since embraced this concept. Though most do not use exclusive right-of-way, projects in cities such as Montreal, Quebec, and Vancouver, British Columbia have turned toward advanced technologies, in lieu of exclusive facilities, to achieve higher bus performance.

The Return of Bus Rapid Transit to the USA

During the late 1970s, BRT made a comeback to the USA with the implementation in Pittsburgh,

Pennsylvania of the first of three major segments of its busway system. In 1977, the 4.3-mile South busway became operational followed in 1983 by the 6.6-mile East Busway with a 2.3 mile extension in 2003; in 2000, the West busway – 5 miles in length – officially opened. This busway system, combined with several new Light Rail Transit projects, has produced an integrated, multimodal system for the greater metropolitan Pittsburgh area [14]. Bus rapid transit success stories in cities such as Curitiba, Ottawa, and Pittsburgh, coupled with continuing congestion and air pollution in urban areas have sparked a renewed interest in the bus rapid transit concept. In 1998, the US Department of Transportation's Federal Transit Administration initiated support for ten BRT demonstration projects, which helped generate further interest in bus rapid transit [15–17].

Contents of This Entry

This entry begins with a discussion of institutional issues associated with the implementation of bus rapid transit systems from a macroscopic perspective. Initially, issues were organized into categories including, for example, intergovernmental and interorganizational, political will, and land use. The subsequent discussion of each category follows with a listing of specific institutional issues within each category.

The entry then turns to a more focused look at specific institutional issues that, based on experience, stand out from other issues relative to the following two criteria: level of importance and level of difficulty to resolve. Specific examples are provided in this section of the entry to illustrate issues.

Institutional Issues: A Broad Perspective

The implementation of bus rapid transit systems traverses numerous stages consisting of system design, development, testing, evaluation, and deployment culminating in a completed and fully operational system. Moreover, all these activities take place in a context with organizational stakeholders participating at various levels. In fact, an overriding theme running through the BRT implementation process is the notion of stakeholders, their agendas, and the relationships among them. As each stage of BRT implementation proceeds through its more technological, design, and operational aspects, questions may arise concerning the effects of actions taken or policy decisions made, which are often of a nontechnical nature and usually referred to as *institutional issues*. These less-technical and less-operational issues, which are numerous and diverse, need to be considered and effective arrangements made that address them to successfully implement a bus rapid transit system.

Bus rapid transit systems will not necessarily experience the same set of institutional issues because each BRT deployment will be affected by local and regional factors. Moreover, even when the same issues arise in different settings, there will likely be local and regional site-specific differences. The importance of identifying and working out such issues should not be underestimated as they do contribute to the overall success of implementing bus rapid transit systems in terms of how transit operations and quality of service for passengers are enhanced.

Institutional issues may be grouped into the following general categories [6]:

- Intergovernmental and Interorganizational
- Intra-agency
- Political Will
- Public Relations and Marketing
- Funding and Finance
- Labor and Human Factors
- Safety and Liability
- Land Use and Planning
- Physical Environment

Intergovernmental and Interorganizational

It is rarely the case that a transit agency can develop a bus rapid transit system without the coordination and cooperation of multiple agencies and often overlapping governmental jurisdictions. Even if this were possible, there is benefit in seeking the cooperation and support of other agencies. However, the multi-jurisdictional and/or multi-stakeholder aspects can make the process of decision-making and implementation more complex as each stakeholder usually brings their own philosophies, priorities, and agendas to the table. Achieving agreement among all affected stakeholders – whether political jurisdictions or other transportation organizations – often proves to be

a difficult task. To have a system that works effectively requires the transit agency to achieve agreement with localities and other agencies on infrastructure, operations, and responsibilities.

When planning for the deployment of bus rapid transit systems, there are, at a minimum, two distinct types of stakeholders with primary roles. One is the local and/or regional transit agency whose interest lies foremost in reducing its own costs while also enhancing the quality of transportation services that it delivers to its passengers. The other primary stakeholder is the local and/or regional highway and traffic department along the route the transit agency's bus runs and this latter stakeholder could include multiple operators depending on whether the bus runs through multiple political jurisdictions. Other stakeholders with a role to play in the implementation of bus rapid transit might also include the following agencies and/or organizations [18]:

- Municipal environmental, health, and urban development and public works departments
- Construction industry and other potential industry supporters
- Regional and/or metropolitan planning organizations
- State or provincial department of transportation
- Relevant national or federal transportation agencies, for example, in the USA such agencies include the Federal Transit Administration and Federal Highway Administration
- Advocacy groups, for example, proponents of competing or complimentary rail projects
- Motorists and their representative organizations
- Economic development agencies
- Business and merchant associations
- Neighborhood or corridor resident associations
- Traffic and transit law enforcement
- Public transportation experts and consultants
- Nongovernmental organizations
- Public transportation passengers, for example, the Bus Riders Union in Los Angeles, California
- Nonmotorized transportation users
- General public

The significance of these stakeholders' roles and influence depends on local and regional conditions encompassing the bus route/traffic corridor where the bus rapid transit system is to be implemented.

Typically, a public transit agency will interface with other government agencies during regular service discussions; however, these interfaces become more critical with the development of a bus rapid transit system; it is typical for a public transit agency to need to coordinate with an organization it had not worked with prior to the bus rapid transit project. These agreements should set out agency and staff responsibilities giving particular attention to the clarification of roles. Achieving consensus, let alone agreement, among all affected stakeholders, whether political jurisdictions or other transportation organizations may at times prove to be a challenging and possibly difficult task. To have a system that works effectively requires the transit agency to achieve agreement with localities and other agencies on infrastructure, operations, and assignment of responsibilities. However, the primary objectives of transit agencies – to provide high-level, high-quality service for their customers at minimum cost – may conflict with the objectives of highway and traffic agencies whose performance is often judged more on enhancing vehicle-moving than people-moving capacity. These often-competing objectives can complicate the implementation of bus rapid transit strategies and may require significant coordination and cooperation if multiple transportation and traffic agencies are involved. An example of conflict of objectives occurs when a BRT project is planned to operate in mixed traffic on public running ways such as when working to achieve the operational benefits of BRT service, preferential treatment on the running way is often required.

The selection and incorporation of new BRT infrastructure may also prove difficult. For many projects, public transit agencies are "tenants" of streets or highway departments, often dependent on the cooperation of the roadway operator for the right to use their infrastructure such as the roadway, signal poles and boxes, etc. Many BRT strategies also utilize infrastructure, which not only needs to be incorporated into the existing roadway facilities, but must be operated and maintained as well. With new infrastructure come additional financial responsibilities. Reaching agreement on acceptable designs, and operational and maintenance responsibilities would likely involve coordination among these agencies.

Bus rapid transit operations will be effective only if laws and regulations regarding transit prioritization are enacted, adhered to, and enforced. Effective enforcement carries with it financial responsibilities that may be thrust reluctantly upon local jurisdictions. Infrastructure and enforcement are two factors vital to the success of BRT, which often lie outside the control of the transit agency. Enlisting the support of the affected parties in these two areas may ultimately determine the success and effectiveness of the BRT system.

Bus rapid transit prioritization may also occur at the expense of other roadway users such as in the case of queue jump lanes. This issue will require discussion and agreement on where and how these preferences should be given, while considering its impact on existing roadway operations. Any impacts to existing services will require the consent and support of highway agencies or street departments, and local governments.

Finally, in attempting to make a seamless transit system, BRT services should be coordinated with neighboring transit agencies. This may require them to revise their operations and schedules to provide better feeder services for the BRT system.

The number and complexity of the agreements will depend upon the type of facility and the governmental organization(s) in the area. There are generally a number of elements of the system that are out of the control of the transit agency. Cooperation among agencies is critical to the successful introduction and operation of a BRT system. In these cases, it is necessary to define and codify these responsibilities. Intergovernmental agreements will be required with a number of different agencies covering items such as right of use (how long, conditions for extension or termination of agreement, state in which the facility is returned to the appropriate agency, legal responsibility, watering maintenance of landscaping, maintenance of running ways, trash collection, graffiti removal, advertising, enforcement, signal timing, lighting). In some cases, local or state laws may be enacted, repealed, or modified to implement various BRT elements or practices, such as the use of the BRT facility by emergency service vehicles.

A specific example to illustrate this type of institutional issue brings together technological aspects, operational plans, and institutional concerns of implementing bus rapid transit. For Los Angeles' Wilshire-Whittier Boulevard Metro Rapid service, which opened in 2000, the Metropolitan Transportation Authority (MTA) implemented a number of bus rapid transit features as elements of its Metro Rapid service including transit signal priority along the heavily traveled corridor, which traverses the cities of Santa Monica, Beverly Hills, and Commerce in addition to the city of Los Angeles and each of these municipalities controls traffic signal operation within their respective jurisdictions. Moreover, along the corridor, the municipal boundaries are such that the city of Los Angeles is interspersed among the other three municipalities in a noncontiguous fashion. Thus, for the Wilshire-Whittier corridor, MTA and the four traffic signal operators, that is, the local municipalities, are the primary stakeholders. Initially, transit signal priority was implemented only within the city of Los Angeles as the other cities wanted demonstrative proof of transit signal priorities' benefits before relinquishing control over the operation of traffic signals in their jurisdictions. To date, transit signal priority still remains implemented only in the city of Los Angeles while negotiations between MTA and the other jurisdictions continue.

The following list summarizes intergovernmental/interorganizational institutional issues:

- Integration of multiple priorities, objectives, and agendas
- Impacts of BRT on roadway operations
- Streets/highway departments "relinquishing" control of their infrastructure
- Agreement on performance measures
- Maintenance responsibilities for shared infrastructure and hardware/software
- Responsibility for enforcement on bus lanes/busways
- Institutional fears of new technologies
- Coordination on selection and implementation of technologies
- Coordinating other transit agencies' services and BRT operations

Intra-agency

Institutional issues may arise not only among transit agencies, political jurisdictions, and highway traffic

agencies, but also internally within an individual transit agency. Concerns over preferences in funding and scarce resources, the delegation of responsibilities, and increased responsibilities for staff may result in internal resistance and morale issues for a transit agency. Unless there are additional funding sources available, increased spending on one route will usually mean decreased funding on others.

Bus rapid transit systems may require additional resources to support the service offered. Additional operations, new technologies, new vehicles, and new infrastructure will require training and maintenance. Achieving agreement on roles and responsibilities may be difficult if employees are merely required to shoulder additional duties and responsibilities for BRT without additional compensation or support.

Many transit agencies may still be unfamiliar with at least a portion of available BRT strategies and agencies may need time and resources to locate or develop both design and operational standards for many of these strategies. Initiating BRT service may also require additional work to reschedule existing services to support the BRT system. As many BRT systems will operate as trunk lines, feeder services will need to be coordinated to achieve the full benefit of the system.

Even gaining internal agreement on what strategies should be implemented, what fare structures should be used, and what technologies are appropriate will again require time and resources. Many agencies will need additional time to identify and digest best industry practices for these issues. Even then, identifying and attempting to accommodate a transit agency's departments' needs may cause internal conflict. As new strategies may affect the duties of department staff, it is vital that they are consulted and strategies are selected with their concerns in mind.

The following list summarizes intra-agency institutional issues:

- Concerns (or perceptions) that BRT is given special preference over other transit services
- Defining and agreeing on new roles, responsibilities, and organizational structures to support BRT
- Creation of design and operational guidelines for BRT
- Determining an appropriate fare structure and medium
- Internal coordination on selection of technology
- Coordinating schedules of other transit routes with BRT operations
- Insufficient understanding of the "state of the art" of technologies and how they can be used in BRT operations

Political Will

The deployment of a bus rapid transit system is one of many stages in the process of design, development, testing, evaluation, and finally deployment of a completed system. At each stage, decision-making stakeholders are involved in a variety of ways that impact the specific deployment path a particular bus rapid transit system will take. The decision-makers are by definition major players in the political arena that govern the local jurisdictions in which the bus rapid transit system would operate. The commitment to bus rapid transit by such major players is of crucial importance to the success of a bus rapid transit system.

One concern in the political arena may be whether a proposed bus rapid transit system is a solution in search of a problem, whether appropriate technologies are being used, and whether there is a market for these enhanced bus transit services. Does it result from a technology push or market pull?

To establish and sustain a high level of interest and commitment to BRT, a political champion will likely be required. Whether it is an individual or organizational entity, a political champion would aid in coalition building and sustaining interest in BRT, which could wax and wane with the whims of the political process. The strength and capability of the political champion would help determine if the project could weather the political storms of opposition arising from various quarters, for example, the local business community, the mass media, or local residents. However, gaining such championing decision-makers often requires proof of the operational and quality-of-service benefits of BRT, but political support is required to perform the testing that could result in the quantifiable benefits, resulting in a chicken-or-the-egg dilemma requiring resolution.

There may also be issues regarding legislative restrictions on the procurement of new vehicles that could delay or slow deployment of BRT. Legal issues may also arise as a result of changes in service associated with BRT operation. For example, route changes, the elimination of stops, or lengthening the distance between consecutive stops could potentially present legal challenges.

Many political officials may be reluctant to undertake a bus rapid transit project due to the perceived risks, especially in relation to upsetting powerful special interest groups. For example, motorists and existing public transportation operators may tend to resist such change. Thus political officials may end up playing it safe by avoiding any type of major public transportation initiative that will risk alienating specific stakeholders. However, when officials take the perceived low-risk path of inaction or very slow action, the ensuing political rewards will certainly be reduced [18].

The following list summarizes politically related institutional issues:

- Concerns of BRT being a top down solution
- Perceived or actual competition of BRT with rail transit
- Lack of domestic BRT success stories
- Lack of empirical evidence of BRT's operational effectiveness
- Finding political champions to support BRT
- Concerns over long-term level of interest, potential for waning
- Local and business community opposition to the removal of, or restrictions on, parking spaces for BRT use
- Local and community opposition to BRT
- Concerns over the distribution of the costs and benefits of BRT
- Legal issues associated with service changes
- New vehicle procurement

Public Relations and Marketing

The success of implementing a bus rapid transit system, as with nearly any new product, service, or system, largely depends on how well it is sold to the public, which often requires setting expectations. Setting high, yet realistic expectations is crucial to gain support for BRT. Failure to produce what was promised could lead to disappointment and a loss of public confidence and support. Bus rapid transit may also require a significant public education campaign on interacting with new transit agency strategies, features, and technologies such as bus lanes, signal priority systems, queue jump lanes, and new fare-collection systems. Moreover, the transit agency needs to consider public views about its current performance. Before taking on the additional responsibilities of a BRT system a transit agency must ensure it is performing satisfactorily, or it could face political and public opposition as it embarks on new ventures [19].

The following list summarizes public relations and marketing institutional issues:

- Educating the public on BRT, and managing perceptions and expectations
- Concerns over transit agency's existing performance and reputation
- Concerns over effects of BRT on existing roadway operations
- Educating pedestrians and motorists on interacting with BRT
- Educating users on changes in and uses of multiple fare structures

Funding and Finance

During the 1960s and 1970s, interest in BRT in the USA waxed and waned. Though there is renewed interest, the fear of history repeating itself in the USA may still cause concern among transit agencies considering BRT for their communities and lead to their reluctance to embrace bus rapid transit. Though the up-front capital costs for most BRT projects are relatively small compared to other capital-intensive modal alternatives such as rail, transit agencies will still be responsible for the operations and maintenance of the new system. With continued fiscal pressures facing transit agencies, concerns may arise over the long-term financial commitment to bus rapid transit. Similarly, bus rapid transit will also require additional financial commitments for staff, training, and enforcement [19].

The following list summarizes funding- and finance-related institutional issues:

- Concerns over long-term funding commitments to BRT at the state and federal levels

- Concerns about BRT redirecting funds away from existing service or other routes
- Lack of understanding of funding mechanisms available for BRT
- Agency reluctance to expand services due to current fiscal constraints
- Ability to use existing buses or need for new fleet
- Capital costs of BRT
- Cost of operating and maintaining (O&M) new technologies and infrastructure
- Cost of additional staff and/or training to support BRT
- Cost of additional facilities to support BRT
- Cost of and responsibility for enforcement, for example, proof of payment

Labor and Human Factors

Another important stakeholder group that must be considered for bus rapid transit is the transit agency staff, especially bus drivers. What will be the impact of bus rapid transit on bus drivers? With the implementation of bus rapid transit, there could be concerns over additional work and responsibilities without assurances of additional staff, needed resources, and/or pay. Bus drivers would have a direct and potentially the closest connection of all agency employees to any new technologies implemented as part of a bus rapid transit system. How would such technologies affect bus drivers? Would it mean any change in the roles and responsibilities of their job? Could the implementation of a bus rapid transit system mean that some bus drivers would lose their jobs or be replaced by individuals with more familiarity with and experience in the use of certain technologies? Will there be assurances to retrain and reeducate bus drivers to use these new systems?

Another concern of bus drivers could be the use or perceived misuse of technology by transit agency management for driver performance monitoring. Drivers may fear their employers using "Big Brother" privacy-threatening tactics under the guise of improving transit operations and service [19].

The following list summarizes labor-related institutional issues:

- Lack of support from transit agency staff
- Changing role of drivers
- Use of technology, for example, automated vehicle location systems for monitoring schedule adherence
- Different responsibilities between bus rapid transit and non-BRT routes

Safety and Liability

Bus rapid transit may involve new procedures, technologies, or personnel tasks. The potential thus exists for system components not to function as anticipated, raising safety and liability issues. Stakeholders need to consider whether bus rapid transit changes the assignment of risk and responsibility if technologies or strategies do not function as intended. Safety issues regarding pedestrians and motorists and their interaction with bus rapid transit components, such as signal prioritization and queue jump lanes, will also need to be considered and addressed [19].

The following list summarizes safety- and liability-related institutional issues:

- Insurance industry–initiated changes in assignment of risk and responsibility for bus transport
- Potential changes in liability associated with technological and/or operational malfunctions of BRT systems
- Safety issues arising from changing interaction of pedestrians and motorists with new technologies and/or strategies
- Safety concerns of residents along BRT corridors

Land Use and Planning

Large-scale public transportation projects often influence travel patterns and surrounding land uses, over both the short and the long term. Bus rapid transit would be no different, as high-level transit services, which BRT attempts to replicate, have often significantly altered surrounding land uses. However, bus rapid transit may raise concerns over how it fits into a region's overall transportation planning environment and how it will affect local land uses.

Anecdotally most transit planners believe that fixed guideway systems have a positive impact on land use, particularly around the station areas, whereas bus-based systems have at best a neutral impact. Bus-based systems have been shown to have

a beneficial impact at a community level; however, property adjacent to stops/stations is considered less desirable.

One of the biggest concerns of communities developing bus rapid transit systems is convincing them that BRT will provide the benefits that they associate with fixed guideway modes. The advent of BRT systems has challenged this premise. The new BRT systems that have chosen to incorporate a fixed guideway element have demonstrated that bus-based transit systems can have a positive impact on urban form and land values. Although the BRT concept is still relatively new in the USA with only a handful of systems in operation, there is a growing body of evidence that suggests that BRT systems can support existing land users and promote higher density residential, office, and commercial land use, particularly around BRT stations. North American examples of this trend include Boston, Pittsburgh, and Ottawa, where $1,250 million, $302 million, and $675 million of new or improved development, respectively, has occurred. The continuing development of more BRT systems will provide further evidence of this effect; however, as land use improvements tend to lag transit investment, examples of this trend may take a while to be realized [20].

Some BRT systems have benefited by initially developing a number of key stations where land use development potential exists and linking them with transit facilities which incrementally increase to fully exclusive busways. In this way, they could make strategic infrastructural investments at specific locations without the need to improve the whole corridor to the same level.

The following list summarizes land-use- and planning-related institutional issues:

- Coordinating a BRT project with local planning agencies' land use policies
- Gaining community support for transit-oriented development
- Possible reluctance of potential developers to invest along BRT corridors due to a perceived lack of permanence as compared to rail
- Integrating BRT projects into the metropolitan planning process
- Planning requirements such as transportation improvement programs that could delay implementation of a bus rapid transit system
- Need for strong community involvement in planning phases builds support

Physical Environment

The physical imposition of a BRT system may also raise political and institutional challenges. Many project areas, especially in older city centers, may simply lack the physical space to accommodate certain BRT strategies. In other areas, transit agencies may encounter opposition if BRT competes with, or at least is viewed as competing with, other interests for high-value real estate. This may inflate costs or overly complicate operational requirements. Though eminent domain is an option, it usually is an undesirable, drawn-out process. Ensuring there is adequate and obtainable physical space could present problems for certain projects.

Secondly, image is a strong marketing tool for BRT. Many design guidelines suggest making the system unique and easily identifiable. Many projects are included as part of their systems station area improvements. However, these improvements are usually being inserted into existing urban design. Finding station area designs that promote a strong image, while being acceptable to local interests, may be a challenge.

The following list summarizes physical-environment-related institutional issues:

- Availability and acquisition of right-of-way or physical space
- Reaching agreement or consensus on bus stop/station area enhancements
- Need to educate and address public concerns regarding the potential effects of BRT on the physical environment

Institutional Issues: Stakeholder Experience

Transit agency experience has shown that there are specific institutional issues that are primary and stand out from others with respect to the criteria of level of importance and ease of resolution. Eight primary issues are listed below (in no particular order) [21]:

1. Local and business community opposition to the removal of/restrictions on parking spaces for BRT use
2. Availability and acquisition of right-of-way or physical space

3. Integration of multiple priorities, objectives, and agendas
4. Concerns over long-term funding commitments to BRT
5. Impacts of BRT on roadway operations
6. Finding political champions to support BRT
7. Gaining community support for transit-oriented development
8. Educating the public on BRT and managing perceptions and expectations

Integration of Multiple Priorities, Objectives, and Agendas

The integration of multiple priorities, objectives, and agendas often lies at the heart of institutional issues. When several institutions come together to discuss issues of common interest, each brings its own organizational experiences, cultures, and goals. A "win-win" strategy might not always be achievable, but BRT project members need to acknowledge and be thoughtful of other agencies' issues and concerns. Modal biases and agendas have historically infiltrated transportation planning. However, in recent years, with the recognition that multimodal transportation systems tend to be the healthiest, there are greater levels of cooperation. Many transportation organizations, however, still have responsibilities to their respective agencies or jurisdictions, and are still expected to protect their own interests. Though greater cooperation nevertheless must also be accompanied by continuous dialogue to discuss and better understand stakeholders' concerns and by attempts to address them throughout the BRT development and implementation process.

For example, close working arrangements between traffic engineers and transit planners are essential in developing busway and bus lane designs, locations of bus stops and turning lanes, and application of traffic controls. A good program of traffic controls and signage will help ensure safe vehicle and pedestrian crossings of busways and bus lanes. Excessively long traffic signal cycle lengths to accommodate exclusive bus phases should be avoided.

Los Angeles's successful Metro Rapid bus operations on its Wilshire-Whittier and Ventura Boulevard lines are a direct result of cooperation between the MTA and the city's Department of Transportation (DOT). These two agencies found that (1) a modest "advance" or "extension" of the traffic signal green time (or a delay of the red signal time) of up to 10 s per cycle can reduce bus delays with negligible impacts on cross street traffic, (2) bus headways should not be less than 2.5–3.0 min to enable major cross streets to "recover" from the time lost, and (3) far-side stops are essential.

An at-grade busway has fewer traffic impacts on intersecting roads than a typical arterial street. However, relatively light bus volumes require traffic control strategies that ensure safety at grade crossings. Positive protection, such as bus-actuated traffic signals, is essential. However, if accidents persist, gating of bus crossings may be appropriate. The busway should be treated as though it were a high-speed light rail line on a private right-of-way. If there is sufficient conflict among various modes (i.e., vehicles, transit vehicles, and pedestrians), it is important to incorporate gates to reduce these conflicts [1].

Finding Political Champions to Support Bus Rapid Transit

Though public support is critical in implementing a BRT system, it is usually not attainable through transportation agencies alone. Finding a political champion to support a BRT initiative may be critical in gaining public support. Politicians are typically the final decision-makers and often have the clout to produce results. Gaining the ear and voice of influential politicians is one of the most often-cited means of achieving results [19].

Roadway-Related Issues

The following three issues may be covered under the umbrella of *roadway-related issues*:

- Local/business community opposition to removal of/restrictions on parking spaces for BRT use
- Availability and acquisition of right-of-way or physical space
- Impacts of BRT on roadway operations

Bus rapid transit intends to provide the high-quality service associated with rail transit at a much lower cost. In many BRT projects, this is accomplished by providing buses with exclusive or nearly exclusive right-of-way, so operations are not affected by urban street congestion. However, obtaining the required right-of-way may be

difficult. Most BRT projects operate, for at least a portion of their route, in developed urban areas where physical space for transportation improvements is typically not in abundance. In several projects, this space comes from currently utilized roadway lanes or from existing parking lanes. Operators of the roadway facilities (typically municipal streets departments or state departments of transportation) used for BRT projects will be interested in how BRT operations would affect their facilities. In cases where projects look to utilize roadway space that is currently on-street parking, businesses and residents may be opposed to the "loss" of parking, even if it is only for peak-period directions and times. For example, at BRT stops/stations the use of queue jump lanes and/or bus bulbs may also be considered. The use of these design attributes in order to improve the level of service may, however, conflict with concerns of the local business community over its opposition to the removal of or restrictions placed on parking space availability that may be necessary to accommodate such operational and service plans for BRT. Therefore one of the major institutional considerations in assessing where BRT is a realistic alternative for specific corridors or roadway facilities is the availability of physical space to accommodate BRT operations. Proper consideration must be given to identify whether there are competing interests for space and how BRT operations may impact these facilities [19].

Concerns over Long-Term Funding Commitments to BRT

Concerns over long-term funding commitments to BRT include it merely being the popular favorite and the implications for transit agencies should the BRT concept fall out of favor. Some BRT projects will require a great deal of capital investment, often requiring transit agencies to shoulder the risk of having greater capital to maintain without recovering sufficient additional revenue to cover those costs. Whether these are items that a transit agency can afford to operate and maintain, may cause reluctance on the part of transit agencies to embrace BRT [19].

Gaining Community Support for Transit-Oriented Development

Allaying the fear of the unknown is often a responsibility that must be borne when presenting an untested concept to the public. Many BRT projects have incorporated land use strategies to encourage and reinforce transit usage. However, for most outside of the transportation and planning communities, the concept of transit-oriented development (TOD) is new. For many, higher density and mixed use equals more crowding and greater congestion. Attempting to obtain public support for TOD may be a challenging undertaking, especially if there are not many local examples to aid the public's understanding. Proactively educating the public on the underlying objectives of TOD may assist a transit agency in avoiding public opposition to it [19].

Educating the Public on Bus Rapid Transit, and Managing Perceptions and Expectations

This issue may be critical in maintaining continued support of and interest in bus rapid transit. Agencies must perform a balancing act on this issue. For BRT to be embraced by both the public and the decision-makers, the concept must be "sold" to them but it must be sold in the correct manner and amount. Setting unrealistically high expectations can lead to disappointment and a loss of support both from the public and from the decision-makers. It is important that balance be maintained between the "hype" and actual results.

Future Directions

Throughout the world, bus rapid transit systems continue to be implemented, with more than 135 systems in over 28 countries on 6 continents and 90 cities in North and South America, Europe, Asia, Australia, and Africa in both the developed and developing worlds. In the USA alone, there are nearly 60 existing BRT systems with significant progress made in the number of implemented systems in the last 12 years alone, which marks a special milestone year in the history of BRT in the USA because 1998 was the start of the most recent resurgence of interest in the USA in bus rapid transit with the US Department of Transportation's formal initiation of and support for a US BRT Demonstration Program.

BRT has shown that it is indeed a viable rapid transit mode within the USA. The strength of the mode lies in its diverse range of BRT strategies and its flexible and incremental character of deployment that allows transit agencies to customize their BRT system to

the local environment including institutional concerns, available right-of-way, or traffic conditions.

For example, agencies with both budget and time resource constraints and little, if any, additional right-of-way capacity may consider a BRT system modeled after Los Angeles's Metro Rapid service. The Metro Rapid uses lower-cost strategies including ITS technologies (transit signal priority systems), frequent headway-based service, a branded and unique identity for the buses and bus stops, low-floor buses, real-time passenger information systems, and a simple route structure with fewer stops to minimize total travel time and enhance travel time reliability on mixed traffic urban arterials. If additional right-of-way capacity is available, agencies may want to consider implementing services on dedicated bus lanes within existing roadways, such as the EmX Line along the Franklin Avenue corridor between Eugene and Springfield, Oregon, where a traffic lane was converted for BRT use. Another example is the Healthline BRT system along the Euclid Avenue corridor in Cleveland, Ohio, where one traffic lane per direction along its 4.5 mile long corridor was removed to build a bus lane within the median. With still more available right-of-way, on the high end of the roadway capacity continuum are exclusive running ways, such as the Metro Orange Line in Los Angeles built along a 14-mile former rail right-of-way owned by MTA. Such systems offer the greatest potential for achieving high speeds and high levels of travel time reliability required for and desired by public transit choice riders.

The next decade will continue to see more BRT systems implemented on an international scale especially in the developing world. In the USA, BRT will continue playing a major role in transit systems throughout the country. Cain A, et al. [22] have suggested that if current trends continue in pioneering BRT cities such as Los Angeles, which has already implemented a network of approximately 25 Metro Rapid BRT Lines beginning with its initial deployment of the Wilshire-Whittier and Ventura Boulevard Lines in 2000, the next major challenge will be transitioning from individual BRT corridors into integrated networks of BRT routes. Such expansion offers transportation planners and engineers the opportunity to increase the benefits of BRT from the corridor level to the city or regional level, enhancing public transit ridership that helps improve mobility and air quality, reduce congestion, and promote economic growth. Careful integration of such networks with existing BRT and conventional bus services as well as non-bus transit modes will be crucial to achieving a successful transition. Nonetheless, in the context of a BRT network as opposed to an individual BRT corridor, the institutional structure may experience changes and it is possible that additional institutional issues heretofore not identified may arise or already existing issues may be exacerbated, which of course will need to be addressed as part of any successful BRT network implementation process.

Acknowledgments

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Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues

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Article Outline

Glossary

Alternatives analysis Evaluation of different transit choices available, usually requiring cost-benefit analysis, life cycle costing, and sensitivity analysis.

Branding Name, term, design, symbol, or any other feature that identifies a service or product.

Bus corridor A street or highway featuring bus priority measures, such as bus lanes or busways or traffic signal priority.

Bus lane Street or highway lane(s) with priority designation for bus public transport services.

Bus priority Infrastructure or traffic signal measures to speed up bus public transport services, especially at intersections or junctions.

Busway Street or highway lane(s) exclusively designated for bus public transport services.

Comfort The capacity to give physical ease and well-being. In public transport, it is usually related to the provision of adequate space, soft ride, easy circulation, and adequate information for passengers.

Commercial speed Distance traveled divided by the time, as perceived by the passengers of the public transport system. It includes time spent at bus stops or stations, intersections or junctions, and the time traveling between them.

Externalities An economic effect that is not reflected in market prices. In public transport, this term usually refers to travel time, air pollution, road fatalities and injuries, and other effects on people and the environment.

Fare collection Collection of entrance fee in a public transport service. It may include direct access to the service or tickets or passes to travel.

Headway Time interval between two consecutive transit vehicles.

Intelligent transport system (ITS) Is an umbrella term for a range of technologies including processing, control, communication, and electronics that are applied to a transportation system.

Paratransit Is an alternative mode of flexible passenger transportation that does not follow fixed routes or schedules. It includes informal services as well as formal services provided for users with special needs, such as elderly and disabled.

Passenger capacity Number of passengers that can be accommodated in a vehicle, station, service, or section of the transport system. Can be measured in units of space (passengers per square meter), vehicles (passengers per bus), or time (passengers per hour per direction).

Peak section load Number of passengers riding inside the transit vehicles in the heaviest section of the public transport system and direction per unit of time, usually 1 h.

Public transport Is a shared passenger transportation service which is available for use by the general public. Also known as public transportation or transit.

Public–private partnership Describes a government service or private business venture which is funded and operated through a partnership of government and one or more private sector companies. These schemes are sometimes referred to as PPP or P3. In public transport, this term usually describes the service or concession contract for transit provision, which may include development of infrastructure and vehicles.

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Rapid transit A system of public transport in an urban area, using a combination of infrastructure, vehicles, operations, and information technologies to provide fast and reliable service.

Reliability Capability of being relied on; dependability. In public transport, this refers to the provision of timely services, with low variance in arrival and travel times.

Service operation plan Public transport routes, schedules, and itineraries, preferably planned in advance and centrally controlled to provide service according to the user needs.

Traffic signal Signaling devices positioned at road intersections, pedestrian crossings, and other locations to control competing flows of traffic. Also known as traffic lights, stoplights, traffic lamps, traffic signals, or semaphores.

Transit-oriented development (TOD) Urban area designed to maximize access by public and nonmotorized transportation to encourage transit ridership. A typical TOD has a rail or bus station at its center, surrounded by relatively high-density and mixed used development. It usually has adequate facilities and attractive street conditions for walking and cycling, good connectivity, and uses traffic calming and parking management measures.

Definition of the Subject and Its Importance

Bus rapid transit (BRT) can be defined as a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways, and information technologies into an integrated system with strong identity [1]. Complete BRT systems offer fast, comfortable, and low-cost urban mobility [2]. BRT is an evolution of bus priority measures, such as designated busways and bus lanes, which were proposed, and in some cases implemented, as early as 1937 throughout the world [3]. The expression BRT was initially used in the United States in a 1966 study [4]. The concept gained popularity in Latin America after the successful upgrade of busways in Curitiba, Brazil, to full-featured BRT in 1982 [5]. The high performance, low cost, and rapid implementation of this system, and its adaptations to Quito, Bogotá, Mexico City, Beijing, Jakarta, Los Angeles, Beijing, Istanbul, and Guangzhou, among other cities, made the idea attractive for urban transport planners throughout the world. As of January 2011, there were about 118 cities with BRT or bus corridors, with 97 of the cities entering into the list in the last 10 years, and at least 80 cities building, designing, or planning BRT systems [6]. BRT is an attractive option for public transport delivery, applicable to a wide variety of conditions – from very low to very high passenger throughput, and should be considered in alternatives analysis in most transit corridors. Critics of BRT indicate that these systems are not permanent, use precious surface space, and exhibit operational and cost issues as compared with rail [7]. BRT implementation requires strong political leadership, sound technical planning, and adequate funding levels [2, 8].

Introduction

The concept of BRT is not new [3], but it has only being extensively deployed around the world in the last decade [6]. The growth may be attributed in part to the success of Curitiba [5] and its adaptations in different parts of the world [2, 3]. In general, BRT systems exhibit low cost, rapid implementation, and high performance, with significant positive impacts [2, 9].

Interesting trends are emerging in the BRT industry [6], such as the implementation of citywide integrated bus systems based on BRT, improved processes for private participation in operations, increased funding from national governments, and growth of bus manufacturers and technology providers. Technological developments in vehicles and information systems are also improving the quality, performance, and impact of BRT [9].

Despite the growth, there are some outstanding issues: BRT does not have a single meaning and image and it is often regarded as a "second best" as compared to rail alternatives [2]. Its ability to foster urban development and the use of space designated for cars are often questioned, as well as its actual costs and impacts [7]. In addition, several systems in the developing world suffer problems resulting from poor planning, implementation, and operation, due to financial, institutional, and regulatory constraints [8].

This entry discusses the concept, its history, and expected trends. In the first section the concept of BRT is developed. The following sections show the

history and current status of BRT in different geographical regions of the world – the United States and Canada, Latin America, Europe, Australia and Oceania, and Asia. The final section indicates future directions.

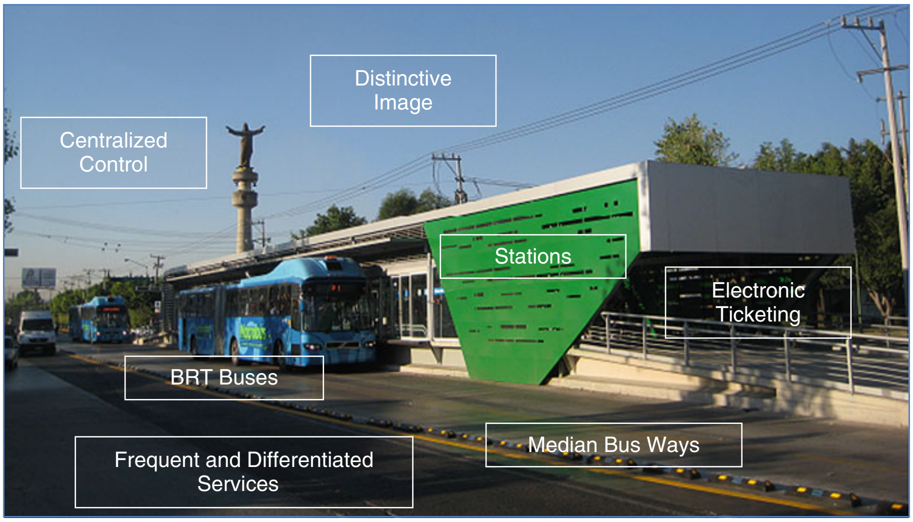
BRT Components, Characteristics, and Impacts

Components of BRT include [9], running ways, stations, vehicles, fare collection, intelligent transport systems (ITS), service operation plans, and branding elements. There could be different degrees of complexity of each one of these elements, resulting in varied system performance characteristics and system impacts. Performance characteristics include commercial speed, passenger capacity, capital and operational productivity, and costs. Impacts of BRT encompass user perception, travel time, reliability, comfort, and externalities – air pollution, road safety, physical activity, and urban development, among others.

Advanced BRT systems typically involve integration of (see Fig. 1, list adapted from [1, 2, 9]):

- Median running ways for exclusive use of the BRT system buses which are separated from the rest of the traffic through raised curbs (right of way A or B, according to the classification by Vuchic [10]).
- Stations with off-board payment and platforms with level access for boarding to the buses.
- Large buses with multiple doors, special design features, and lower emission levels than conventional buses.
- Use of advanced electronic ticketing systems, such as contactless fare cards, integrated to other applications.
- Several information technology applications for centralized control – such as automatic vehicle location (AVL) and dispatch systems, and improved user information systems – variable message signs in stations and buses to indicate next bus and next station in real time, and provide public announcements; online and personal data appliance providing routing and schedule information, among other applications.
- Combined service plans according to the passenger demand characteristics, including high frequency trunk line services combined with feeder services, as well as accelerated and express bus services.
- Distinctive image differentiating running ways, stations, buses and overall service from other bus services and transit applications in the city.

Few systems encompass all these components. Each component is adapted to the local conditions and the service needs [1], as well as budgetary constraints.



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 1
BRT system characteristics (Guadalajara, México, Macrobus BRT system, CTS Mexico 2010)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 1 Maximum values for some performance indicators in selected BRT systems

Performance indicator	Definition	Value (year)	System, city (date)	System features
Commercial speed	Distance/time as perceived by the user on board (km/h)	42 km/h (2011)	Metrobüs, Istanbul, Turkey	Fully segregated busway on expressway, stations every 1.1 Km [11]
Peak section load	Passengers/hour/direction (pphpd)	45,000 pphpd (2011)	TransMilenio, Bogotá, Colombia	Median busway, level access stations with five platforms, overtaking lanes and combined services –local, express, seven standees per square meter, dense urban area [12]
Infrastructure productivity	Passengers/kilometer of busway	35,800 (2011)	Guangzhou BRT, China	Median busway, with long station, overtaking lanes, open operation 40 routes, very dense urban area [13]
Capital productivity	Passenger boardings/bus/day	3,100 (2010)	Macrobús, Guadalajara, México	Median busway, overtaking lanes relatively dense, mixed use urban area [8]
Operational productivity	Passenger boardings/bus kilometers	13.2 (2010)	Metrovía, Guayaquil, Ecuador	Median busway, dense urban area, very low fare (USD 0.25 per trip) [8]

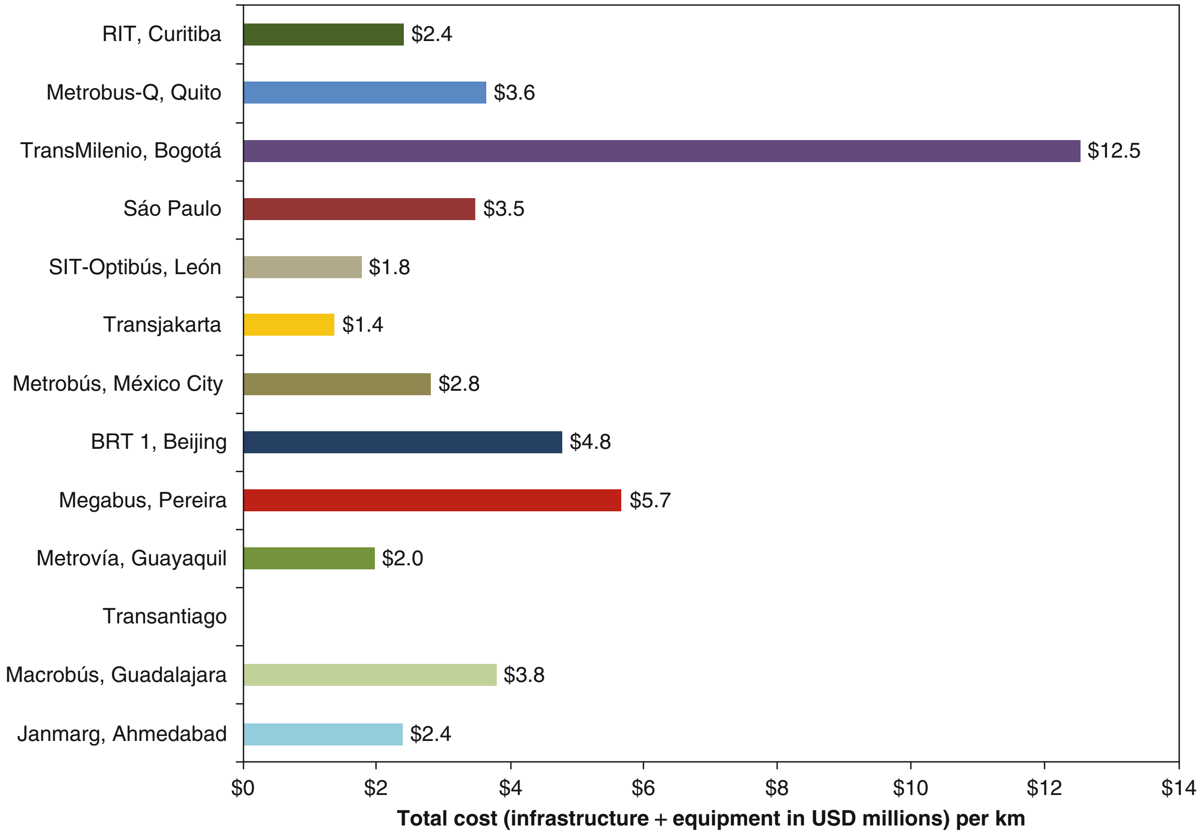
As a result, performance characteristics are varied. Table 1 presents the maximum values of some performance indicators observed:

BRT capital costs are in the range of one tenth to one third of comparable rail systems [2, 14]. BRT costs depend on the selection of system components and performance requirements. Figure 2 shows comparison of capital costs for some systems in the developing world; most systems have been built and equipped at a cost between 1 and 5 million USD per kilometer. The higher cost of the Bogotá BRT system reflects the investment to achieve very high peak load (45,000 pphpd) and commercial speed (28 km/h) [8].

Regarding system impacts, most systems have resulted in higher passenger demand than expected [2, 9, 14]; user satisfaction is frequently high [15, 16]; travel times are usually reduced as a result of higher commercial speeds than buses in mixed traffic [2, 8, 9], reliability increased due to the supporting infrastructure and communication technologies [9], and there is documentation on positive impacts for several systems regarding reduction of crashes, pollutant emissions, and improved urban environments [9, 14, 17, 18] Concerning comfort, most systems in developing countries use very high occupancy standards and may not be considered comfortable [8]; this is a result of financial restrictions that require most transit operations in developing cities to be self sustainable. As a result, productivity levels need to be very high. Critics of BRT often cite comfort issues when comparing bus systems with rail [7].

BRT Status Around the World

BRT is currently a key component of an effective urban transport policy to address congestion, pollution, and road accidents. A survey of BRT around the world [6] indicates that there are about 118 cities with BRT or bus corridors. The existing BRT and bus corridors as of January 2011 comprise about 280 corridors, 4,300 km, 6,700 stations, and use 30,000 buses, serving about 28 million passengers per day [6]. As of January 2011, about 49 new cities were building BRT systems, 16 cities were expanding their corridors, and 31 cities indicated they were at in initial planning stages [6]. What used to be unusual in the early 1990s became common in 2010. Most cities have either developed BRT or bus corridors, or have considered their inclusion in their transportation improvement plans.



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 2
Capital costs per kilometer for selected BRT systems (2009) (Source: Hidalgo and Carrigan [8])

Table 2 presents a regional distribution of BRT and bus corridors around the world, which shows its presence in all continents. Latin America has about one fourth of the cities in the world, but concentrates two thirds of the ridership. There are a very high number of cities and kilometers in Asia, which is the fastest urbanizing region in the world. Usage in Europe, the USA, and Canada is comparatively low in relation with the total kilometers reported. Only two cities in Africa have introduced BRT: Johannesburg, South Africa, and Lagos, Nigeria. The only intercontinental BRT is in Istanbul, Turkey, crossing the Bosphorus Strait.

Figure 3 shows the number of cities introducing BRT or bus corridors since 1970, as well as the total cumulative number of cities. Most cities in the list (97), introduced BRT or bus corridors in the first decade of the twenty-first century. The highest number of cities introducing BRT or bus corridors in the last decade is in China, followed by Indonesia, and the Latin American region.

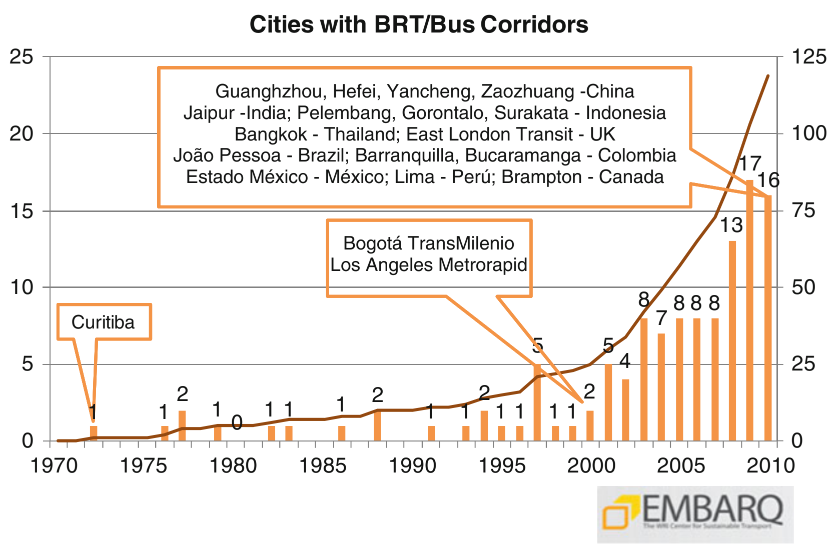
Some trends are emerging in the BRT Industry:

- Implementation of integrated transit systems based on BRT: The initial phase of implementing isolated corridors is evolving toward citywide systems integration, often including other modes of transport like Metro (Sao Paulo [19], Santiago [20], and Guangzhou [13]); Light Rail Transit (Guadalajara [21], Monterrey); and conventional buses (Sao Paulo [19], Santiago [20], and Bogotá [22]).
- Improved processes for private participation in operations: Most BRT systems in developing countries operate under public–private partnership agreements, using performance-based concession contracts which are awarded either through competitive tendering – with some provisions to include

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 2 Regional distribution of BRT and bus corridors as of January 2011

	Cities	Corridors	Kilometers	Stations	Buses	Passengers/day
Africa	2	2	47	63	363	290,000
Asia	33	85	1,306	1,658	6,590	6,289,531
Europe	25	32	291	609	781	629,369
Europe/Asia	1	2	43	33	300	700,000
Latin America and the Caribbean	32	90	1,330	2,687	18,656	17,591,945
Oceania	5	12	324	142	1,411	345,800
USA and Canada	20	57	993	1,485	1,993	1,013,901
Total	118	280	4,335	6,676	30,094	26,860,546

Source: EMBARQ BRT/Bus Corridors Database [6]



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 3 Cities with BRT/bus corridors 1970–2010 (Source: EMBARQ BRT/Bus Corridors Database [6])

incumbent operators, or direct negotiations of new concessions with existing private providers [8].

- Increased funding from national governments: BRT systems are eligible for funding from the national or federal governments in several countries, like Mexico – through the national fund of infrastructure FONADIN [23]; Brazil – through the Program for Growth Acceleration PAC 2 Mobility in Large Cities [24]; and India – through the Jawaharlal Nehru National Urban Renewal Mission JnNURM [25] and the National Urban Transport Policy [26], among others.
- Growth of bus manufacturers and technology providers: Commercial vehicle manufacturers and information technology providers are increasing their activity, especially in emerging economies like Brazil, China, India, and Indonesia.
- Technological developments in vehicles and information systems are also improving the quality, performance, and impact of BRT [9]. Advanced

technologies include cleaner fuels – Compressed Natural Gas CNG, Ultra Low Sulfur Diesel ULSD, Biofuels, Hydrogen; improved propulsion technologies – hybrid drive trains, electric; emissions posttreatment – catalytic converters, particulate filters; improved central dispatch and real-time control systems – automatic vehicle location (AVL) and operations control; enhanced fare collection systems using electronic ticketing and contactless fare cards; improved user information systems – variable message signs, communication with personal wireless devices for routing, information of next buses and public announcements, among others.

Despite the growth, there are some outstanding issues:

- BRT does not have a single meaning and image – a broad spectrum of applications, from improved bus service on mixed traffic to totally segregated systems, are considered BRT [1, 2, 9].
- It is often regarded as a "second best" as compared to rail alternatives without a fair evaluation or alternatives analysis [2, 7, 10, 14].
- Its ability to foster urban development and the use of space designated for cars are often questioned, as well as its actual costs and impacts [7].

Several systems in the developing world suffer problems like [8]

- Rushed implementation – several components incomplete at the time of commissioning, but gradual improvement over time has been observed
- Very tight financial planning – user fares are not defined technically generating risks in some systems
- Very high occupancy levels – the adopted standard of 160 passengers/vehicle for articulated buses is not acceptable by the users
- Early deterioration of infrastructure – lack of road surface reinforcement or problems in design and construction result in maintenance issues
- Delayed Implementation of fare collection systems, which often require longer timetables than initially expected and need very tight supervision
- Insufficient user education for initial implementation and system changes

These issues are often the result of poor planning, implementation, and operation, due to financial, institutional, and regulatory constraints; they are not intrinsic to the BRT concept [8].

BRT in the United States and Canada

According to Levinson et al. [3], the idea of using buses to provide mass transit is not new. Plans for bus systems, displaying the current understanding of BRT, were proposed as early as 1937, when a "plan called for converting three west side rail rapid-transit lines to express bus operation on super highways with on-street distribution in central areas and downtown," in Chicago. Similar major initiatives for buses on reserved lanes on freeways were proposed in a 1956–1959 Washington D.C. Plan, a 1959 St. Louis Plan, and a 1970 Milwaukee Plan [3].

Several research studies, indicating the potential of BRT and suggesting guidelines for the design of bus facilities were completed between 1966 and 1975. Levinson et al. [3] indicate that "most of these planning studies focused on the facility aspects of BRT, often as an adjunct to urban freeways. Little or no attention was given to the station, service, and image/identity aspects of BRT."

The planning emphasis changed in the late 1970s, from bus use of streets and highways toward the provision of high-occupancy vehicle (HOV) lanes and light rail transit (LRT) due to environmental and performance considerations [3]. LRT tended to be considered more fully in alternative analyses, due to lack of information on the potential benefits and costs of BRT [3]. More recently, BRT recaptured interest of planners and funding agencies [3]. The Federal Transit Administration (FTA) sponsored a BRT conference in 1998, using Curitiba's BRT system as a model, published major documents highlighting BRT, established a BRT Consortium with 17 supporting cities in 1999, and launched a BRT "Demonstration Program" involving 15 cities [3].

The most important BRT systems and bus corridors in the United States and Canada by January 2011 are presented in Table 3, including date of initial implementation, some features, and estimated ridership. There are 20 cities, featuring 57 corridors and 993 km, serving about 1,013,901 passengers per weekday.

Systems in the United States are not usually displaying full BRT features. The most

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 3 Most relevant BRT systems and bus corridors in the United States and Canada by January 2011

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/ day (year)	Source
Pittsburgh, Pennsylvania	1977	South, MLK East, West Busways	3	31.3	50	103	51,700 (2009)	[6, 9]
Ottawa, Ottawa	1983	Transitway	3	30.0	37	195	97,739 (2008)	[6, 9]
Miami, Florida	1997	South Miami-Dade Busway	1	34.0	30	46	23,000 (2009)	[6, 9]
Orlando, Florida	1997	LYNX Lymmo	1	5.1	22	9	4,475 (2009)	[6, 9]
Chicago, Illinois	1998	Express	3	62.4	154	109	54,742 (2009)	[6, 9]
Los Angeles, California	2000	Metrorapid	21	390.2	650	893	464,600 (2009)	[6, 9]
Oakland, California	2003	San Pablo Rapid	1	23.8	52	26	13,000 (2009)	[6, 9]
Albuquerque, New Mexico	2004	Rapid Ride	1	23.5	30	25	12,430 (2009)	[6, 9]
Boston, Massachusetts	2004	Silver Line	2	11.7	61	62	30,874 (2009)	[6, 9]
Las Vegas, Nevada	2004	MAX	1	12.75	22	20	10,000 (2009)	[6, 9]
Halifax, Nova Scotia	2005	Metrolink	3	39.4	16	15	7,266 (2008)	[6, 9]
York, Ontario	2005	VIVA	5	63.6	59	71	35,300 (2008)	[6, 9, 30]
Los Angeles, California	2007	Orange Line	1	24.65	28	125	62,597 (2009)	[6, 9]
Eugene, Oregon	2008	EmX	1	6.8	18	13	6,200 (2009)	[6, 9]
Phoenix, Arizona	2008	LINK	4	128.0	92	5	2,372 (2009)	[6, 9]
Cleveland, Ohio	2009	HealthLine	1	12.1	36	21	10,591 (2009)	[6, 9]
Kansas City, Kansas	2009	MAX	1	10.2	42	9	4,450 (2009)	[6, 9]
New York, New York	2009	Bx Select Bus	2	26.4	52.7	220	110,187 (2010)	[6, 31]
Snohomish County, Washington	2009	Swift	1	28.9	16	10	4,878 (2010)	[6, 32]
Brampton, Ontario	2010	Züm	1	28.5	17	15	7,500 (2010)	[6, 33]

advanced applications are the Orange Line (Los Angeles, California, 2007, Fig. 4), EmX (Eugene, Oregon, 2008), and the HealthLine (Cleveland, Ohio, 2009). Evaluations of these and other applications in the United States are available in the FTA document "Characteristics of BRT for Decision Makers" [9] and the National BRT Institute [27], a federal funded program.

In Canada, the City of Ottawa, implemented a very interesting concept, the Transitway, a fully segregated corridor with services coming in and out, allowing for direct trips without transfers [9, 28]. Plans to partially replace the Transitway system with Light Rail are underway [29]. The suburban communities of York (2005) and Brampton (2010), in Ontario, also improved transit using BRT.

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 4
Orange Line, Los Angeles, North Hollywood station (Source: Gary Leonard, http://www.metro.net/press/2005/10_october/metro_160a.htm#North)

BRT in Latin America

Many Latin American cities have embraced bus rapid transit as a key component of their transit systems. Curitiba, Brazil, can be considered the cradle of modern BRT [5]. Since the 1970s, Curitiba's administrators have introduced constant innovations to the city's bus-based transit system. Originally, the bus system evolved from conventional buses in mixed traffic to busways, which were fitted with at-level boarding, prepayment, and articulated buses, creating the first full BRT system in the world in 1982 [5]. Later on, the city introduced high capacity bi-articulated buses and the electronic fare ticketing systems.

In 2009, the Curitiba integrated bus system was upgraded, again, with the introduction of the Green Line, its sixth BRT corridor which includes the operation of 100% bio-diesel articulated buses [5]. In 2010, the city also introduced capacity enhancements for one of its existing corridors (Fig. 5). Capacity expansions are underway in all the original corridors.

The success story of Curitiba has been replicated in several cities through the region, with adaptation to the local conditions [34]. Quito replicated the Curitiba concept in 1995, with the use of electric trolleybuses to preserve the environment in its historic downtown [34]. Bogotá, expanded the concept in 2000, using very large stations with passing lanes, combined local and express services, electronic ticketing system and centralized control, achieving extremely high peak loads – over 45,000 passengers per hour per direction (Fig. 6) [35].

The Curitiba, Quito, and Bogotá successes were then replicated, with adaptations, to at least 29 cities (Table 4). As of January 2011, there were at least 91 BRT and bus corridors; 1,300 km; 2,700 stations; and 18,000 buses, serving more than 17 million passengers per day [6]. Latin America has one fourth of the world cities with BRT or bus corridors, serving two thirds of the estimated global ridership [6].

Many other cities in the region, like Buenos Aires, Medellin, Cartagena, Cúcuta, Arequipa, Asunción, Chihuahua, Querétaro, San Juan, and Panamá City, were building corridors or in final planning stages as of January 2011 [6].

The highest concentration of BRT and bus corridors is in Brazil with 16 cities and 828 km [6]. It is important to indicate that most cities in Brazil, outside Curitiba and

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 5
Boqueirao busway in Curitiba integrated system after capacity expansion in 2010 (Source: Municipality of Curitiba 2010)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 6
Bogotá TransMilenio BRT system peak section in Avenida Caracas – station with five platforms, prepayment, level boarding and overtaking lanes for local and express services (Source: TRANSMILENIO S.A. 2001)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 4 Most relevant BRT systems and bus corridors in Latin America and the Caribbean by January 2011

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/ day (year)	Source
Curitiba, Brazil	1972	Rede Integrada de Transporte	6	72	376	2,200	2,260,000 (2010)	[5, 6]
Goiania, Brazil	1976	Rede Metropolitana de Transporte Coletivo	3	35	70	200	200,000 (2010)	[6, 36]
Porto Alegre, Brazil	1977	Prioridade Transporte Colectivo	10	57.2	103	1,300	1,170,000 (2010)	[6, 36]
Sao Paulo, Brazil	1979	Prioridade Transporte Colectivo	10	301.3	602.6	7,604	6,843,664 (2010)	[6, 36]
Juiz de Fora, Brazil	1982	Av. Visconde do Rio Branco	1	5	10	83	75,000 (2010)	[6, 36]
Campinas, Brazil	1988	Prioridade Transporte Colectivo	3	13.4	9	178	160,000 (2010)	[6, 36]
Mauá – Diadema, Brazil	1988	Corredor Metropolitano ABD	1	33	66	233	273,000 (2010)	[6, 36]
Campo Grande, Brazil	1991	Sistema Integrado de Transportes	1	3.2	6.4	89	80,000 (2010)	[6, 36]
Fortaleza, Brazil	1994	Sistema Integrado de Transportes	1	3.6	7.2	86	77,000 (2010)	[6, 36]
Quito, Ecuador	1995	Metrobus-Q	3	42.2	82	531	440,000 (2010)	[6, 8]
Uberlândia, Brazil	1997	Sistema Integrado de Transportes de Uberlândia	1	17	13	78	70,000 (2010)	[6, 36]
Bogota, Colombia	2000	TransMilenio	7	84	144	1,769	1,700,000 (2010)	[6, 37]
Natal, Brazil	2001	Sistema Integrado de Transportes	2	5	19	200	180,000 (2010)	[6, 36]
Leon, Guanajuato, México	2003	Optibus	4	31	61	90	700,000 (2010)	[6]
Monterrey, México	2003	Metrobus	3	101	201	85	125,281 (2010)	[6]
Belo Horizonte, Brazil	2004	Prioridade Transporte Colectivo	2	23.7	47.4	483	435,000 (2010)	[6, 36]
Feira de Santana, Brazil	2005	Sistema Integrado de Transportes	2	3.5	7	83	75,000 (2010)	[6, 36]
Mexico City	2005	Metrobus	3	67	108	275	620,000 (2011)	[6]
Salvador, Brazil	2005	Sistema de Transporte Coletivo por Ônibus	2	4	8	167	150,000 (2010)	[6, 36]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 4 (Continued)

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/ day (year)	Source
Guayaquil, Ecuador	2006	Metrovia	2	63	60	215	300,000 (2010)	[6, 38]
Guatemala City	2007	Transmetro	2	35.0	70	400	400,000 (2010)	[6]
Merida, Venezuela	2007	Transmerida	2	30	34	8	8,000 (2010)	[6, 39]
Pereira, Colombia	2007	Megabus	3	19.15	37	137	115,000 (2010)	[6, 40]
Recife, Brazil	2007	Sistema Estrutural Integrado (L-O)	1	9	28	444	400,000 (2009)	[6, 41]
Santiago, Chile	2008	Transantiago	3	26	52	130	130,000 (2010)	[6]
Cali, Colombia	2009	MIO	6	179.0	358	470	215,000 (2010)	[6, 40]
Guadalajara, Mexico	2009	Macrobus	1	16	27	144	130,000 (2010)	[6]
Barranquilla, Colombia	2010	Transmetro	1	13.4	15	92	32,000 (2010)	[6, 40]
Bucaramanga, Colombia	2010	Metrolinea	1	8.9	24	131	75,000 (2010)	[6, 40]
Estado Mexico	2010	Mexibus	1	16	32	63	63,000 (2010)	[6, 42]
João Pessoa, Brazil	2010	Corredor de Ônibus de João Pessoa	1	2.5	5	111	100,000 (2010)	[6, 43]
Lima, Perú	2010	Metropolitano	2	27	35	627	160,000 (2010)	[6, 44]

Goiania, keep the general model of busways, rather than full BRT systems. There was a major upgrade of the integrated system in Sao Paulo in 2005 [19], which included the introduction of an elevated fully segregated busway – Expresso Tiradentes (Fig. 7). Similarly, Santiago, Chile introduced a major reform in bus services in 2008, which includes several busways, and prepayment in selected stations, but keeps most fare collection off board and has few segregated busways [20].

BRT in Europe

European cities have preserved and enhanced their transit systems in high capacity corridors using metros and tramways mainly, with buses only considered in medium capacity corridors. Heddebaut et al. [45] consider that high capacity BRT configurations do not suit the European context (lack of available space, undesirable urban cuttings, and low demand). These authors prefer the term "Bus with a High Level of Service (BHLS)," rather than BRT, to refer to the European applications introduced in several cities (Table 5). Most applications have bus lanes in congested areas (downtown), sharing the road with taxis and bicycles, and in few cases lanes in expressway (High-occupancy vehicle lanes in Madrid and Grenoble, Metrobüs in Istanbul).

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 7
Expresso Tiradentes, Sao Paulo, Brazil (Source: Sao Paulo Transportes SPTrans 2008)

Case studies compiled by the European Union project COST [46] indicate that BHLS corridors are well adapted to new urban zones, small towns, and medium-sized conurbations [45]. They also allow for a variety of configurations (feeder-trunk and direct services), and permit transformation into tramway systems once there is sufficient demand. Some applications used advanced vehicles, including optical or magnetic or physical guidance (e.g., Castellón de la Plana, Eindhoven, Leeds).

Outside the European Union, the most widely used application is the Istanbul Metrobüs, which connects Europe and Asia in the only intercontinental BRT system (Fig. 8). This system has central busways on expressway (fully segregated BRT), very long platforms, low floor buses (articulated and bi-articulated), and achieves very high commercial speed (42 km/h) and peak throughput (30,000 passengers/hour/direction) [11]. It carries 700,000 passengers per day in a 45 km corridor, under expansion in 2011.

Table 5 shows the most relevant corridors in Europe, including Turkey. There are at least 27 cities in Europe with bus corridors, 35 corridors, 335 km, and 1,083 buses, serving 1.3 million passengers per day (53% in Istanbul) [6].

BRT in Asia

BRT is evolving very rapidly in several Asian countries, such as China [49], Indonesia [50], India [51], and Iran [6]. Applications are very varied, from very basic bus corridors (e.g., Delhi and Pune) to very complete systems (e.g., Ahmedabad and Teheran). Table 6 lists the most relevant corridors as of January 2010.

There are at least 33 cities, with 85 corridors, 1,306 km, 1,720 stations, 6,590 buses, serving 6.3 million passengers per day. Forty-five percent of the cities started operation in 2009 and 2010 and many other cities are building and planning BRT and bus corridors across the region.

One important advance in BRT development is the application in Guangzhou, China (Fig. 9), which uses direct services, with large stations, overtaking lanes and the use of advanced technologies for control and user information [49]. This system features very high throughput (30,000 passengers per hour per direction), with small number of transfers.

BRT in Australia and New Zealand

Australia has a long tradition on BRT, as one of the first world systems, the Adelaide North East Busway started

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 5 Most relevant bus corridors in Europe as of January 2010, including Istanbul, which extends to Asia

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Paris, France	1993	TVM	1	19.5	29	33	65,000 (2009)	[6, 47]
Ipswich, UK	1994	Ipswich Rapid Transit	1	0.5	1	1	739 (2010)	[6]
Leeds, UK	1995	Superbus	2	4.2	8.4	62	31,000 (2005)	[6, 48]
Dublin, Ireland	1997	QBC	1	8.4	17	68	34,000 (2009)	[6, 46]
Rouen, France	2001	TEOR	3	13	52	64	45,000 (2009)	[6, 47]
Utrecht, The Netherlands	2001	TVM	2	8.2	16	42	33,500 (2005)	[6]
Caen, France	2002	Twisto TVR	1	15.7	34	24	48,000 (2009)	[6, 47]
Nancy, France	2002	TVR (GLT)	1	8	30	18	37,000 (2009)	[6, 47]
Amsterdam, The Netherlands	2002	Zuidtangent BRT	1	33	66	80	40,000 (2009)	[6, 46]
Bradford, UK	2002	Manchester Road	1	3.7	7.4	7	5,467 (2005)	[6, 48]
Eindhoven, The Netherlands	2003	Phileas	1	15	30	12	28,500 (2009)	[6, 9]
Crawley, UK	2003	Fastway	2	24	48	23	6,000 (2005)	[6, 46]
Prato, Italy	2004	LAM	1	15	30	120	60,000 (2009)	[6, 46]
Edinburgh, Scotland	2004	Fastlink	2	5	10	55	44,000 (2005)	[6, 48]
Lyon, France	2006	C-Lines	1	4	10	5	4,700 (2009)	[6, 47]
Nantes, France	2006	BusWay (Line 4)	1	7	15	20	21,000 (2009)	[6, 47]
Kent, UK	2006	Fastrack	1	15	30	14	5,726 (2005)	[6, 48]
Luton, UK	2006	FTR train to plane	1	5	2	4	30,000 (2010)	[6]
York, UK	2006	FTR First York	1	5	10	11	5,500 (2010)	[6]
Lorient Triskell, France	2007	BHLS	1	5	15	13	15,000 (2009)	[6, 47]
Maubeuge, France	2008	BHLS - Viavil	1	7.5	14	20	5,000 (2009)	[6, 47]
Toulouse, France	2008	Toulouse BSP	2	11	17	11	13,300 (2009)	[6, 47]
Istanbul, Turkey	2008	Metrobus	2	43	33	300	700,000 (2010)	[6, 11]
Castellon de la Plana, Spain	2009	TVRCAS	1	1	4	2	4,000 (2010)	[6]
Cambridge, UK	2009	Guided Busway	1	25	50	46	36,938 (2005)	[6, 48]
Swansea, UK	2009	FTMetro	1	13.5	27	10	5,000 (2010)	[6]
London, UK	2010	East London Transit	1	20	40	18	9,000 (2010)	[6]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 8
Istanbul Metrobüs, intercontinental BRT system (Source: Dario Hidalgo, EMBARQ, March 2010)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 6 BRT and bus corridors in Asia as of January 2010

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Taipei, China Taiwan	1996	Busways	10	30.3	143	1,680	1,680,000 (2008)	[6, 52]
Kunming, China	1999	Busways	5	46.7	63	156	156,000 (2010)	[6, 53]
Nagoya, Japan	2001	Yutorito Line	1	6.5	9	52	26,000 (2010)	[6]
Seoul, North Korea	2003	Median bus lanes	5	43	73	500	400,000 (2009)	[6, 53]
Jakarta, Indonesia	2004	TransJakarta	10	172.2	241	520	276,643 (2010)	[6, 50]
Beijing, China	2005	Beijing BRT	3	34.5	60	200	200,000 (2008)	[6, 53]
Batam, Indonesia	2005	Bus Pilot Project	2	36	20	22	1,472 (2010)	[6, 50]
Hangzhou, China	2006	Hangzhou BRT	2	18.8	50	104	153,000 (2010)	[6, 53]
Pune, India	2006	Pune BRTS	2	16.5	33	54	54,000 (2010)	[6]
Bogor, Indonesia	2007	Trans Pakuan	2	60	56	30	2,978 (2010)	[6, 50]
Tehran, Iran	2007	Tehran BRT	5	91	114	1,125	1,440,000	[6]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 6 (Continued)

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Changhzou, China	2008	Changhzou BRT	2	41	51	240	240,000 (2010)	[6, 53]
Chongqing, China	2008	Chongqing BRT	1	6	9	10	1,500 (2010)	[6, 53]
Dalian, China	2008	Dailan BRT	1	9	13	87	87,000 (2010)	[6, 53]
Jinan, China	2008	Jinan BRT	4	34.4	46	165	162,750 (2010)	[6, 53]
Xiamen, China	2008	Xiamen BRT	3	48.9	40	177	177,750 (2010)	[6, 53]
New Delhi, India	2008	Delhi BRTS	1	5.8	9	96	95,565 (2010)	[6]
Yogyakarta, Indonesia	2008	Trans Jogja	3	90	76	75	12,702 (2010)	[6, 50]
Zhengzhou, China	2009	Zhengzhou BRT	1	26.6	38	170	84,000 (2010)	[6, 53]
Ahmedabad, India	2009	Janmarg	3	39	61	60	102,013 (2010)	[6, 54]
Bandung, Indonesia	2009	Trans Metro Bandung	1	16	15	10	589 (2010)	[6, 50]
Manado, Indonesia	2009	Trans Kawanua	2	51	39	27	108 (2010)	[6, 50]
Pekanbaru, Indonesia	2009	Trans Metro Pekanbaru	2	74	58	20	5,691 (2010)	[6, 50]
Semarang, Indonesia	2009	Trans Semarang	1	30	53	20	2,560 (2010)	[6, 50]
Guangzhou, China	2010	Guangzhou BRT	1	22.5	26	800	800,000 (2010)	[6, 53]
Hefei, China	2010	Hefei BRT	2	12.7	14	65	65,250 (2010)	[6, 53]
Yancheng, China	2010	Yancheng BRT	1	8	21	20	20,000 (2010)	[6, 53]
Zaozhuang, China	2010	Zaozhuang BRT	1	33	24	20	20,000 (2010)	[6, 53]
Jaipur, India	2010	Jaipur bus	1	7.1	10	20	6,200 (2010)	[6]
Gorontalo, Indonesia	2010	Trans Hulonthanlangi	3	90	84	15	1,920 (2010)	[6, 50]
Palembang, Indonesia	2010	Trans Musi	2	60	106	15	1,920 (2010)	[6, 50]
Surakarta, Indonesia	2010	Batik Solo Trans	1	30	53	15	1,920 (2010)	[6, 50]
Bangkok, Thailand	2010	Bangkok BRT	1	15.9	12	20	10,000 (2010)	[6, 53]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 9
Guangzhou, China, BRT corridor (Source: Karl Fjelstrom [49] http://www.transportphoto.net/photo.aspx?id=7599&c=Guangzhou&l=en)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 7 BRT and bus corridors in Australia and Oceania as of January 2010

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day	Source
Adelaide, Australia	1986	O-Bahn	1	12	3	138	28,000 (2009)	[6, 55]
Brisbane, Australia	2001	Brisbane Busway	3	23.8	21	1,002	242,000 (2009)	[6, 55]
Melbourne, Australia	2003	SmartBus	4	233	56	122	36,200 (2009)	[6, 55]
Sydney, Australia	2003	Busways	3	49.1	58	140	32,400 (2009)	[6, 55]
Auckland, New Zealand	2005	Northern Busway	1	5.9	4	9	7,200 (2009)	[6, 55]

operation in 1986 [55]. Brisbane, Melbourne, Sydney, and Auckland introduced bus corridors between 2001 and 2005 (Table 7). Bus corridors in Australia and New Zealand have very diverse design features, from guided busways (Adelaide) and fully grade-separated bus-only roads (Brisbane, sections of Sydney), to on-street busways (Auckland) and bus lanes (Melbourne) [55].

According to Currie and Delbosc [55], the BRT concept continues to be very attractive in the region with rapid increase in kilometers and ridership, especially on established systems. The authors identify risks in the provision of vehicles and accommodating high patronage growth, but highlight the relative cost-effectiveness. BRT development in Australia and

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 10
Brisbane BRT (Source: Karl Fjelstrom December 2004, http://www.transportphoto.net/photo.aspx?id=1303&c=Brisbane&l=en)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 11
Rea Vaya, Johannesburg's BRT, South Africa (Source: Rea Vaya (2010) http://www.reavaya.org.za/photo-gallery/state-of-the-art/category/1)

New Zealand has exceeded rail in the last decade; nevertheless, rail has received greater attention lately [55].

Brisbane (Fig. 10), exhibits very advanced design features, and recently completed a downtown tunnel.

BRT in Africa

Infrastructure and service development in African cities is beginning to pick up attention by the local authorities, as urbanization and GDP increase. Governments are beginning to recognize the need for organized transit, to replace low-quality informal paratransit services [56].

Two cities, Lagos, Nigeria, and Johannesburg, South Africa, started operations of BRT systems in 2009. Lagos implemented a corridor on the parallel roads of an existing expressway with a length of 22 km, 26 stations, and 220 buses, carrying 220,000 passengers per day [57]. However, it is not considered a full BRT, as the bus lanes are on the kerb side, with some sections on mixed traffic and access to the buses requires stairs [56].

Johannesburg launched a full BRT system in preparation to the Football World Cup in 2009 (Fig. 11). The system is 25 km long (out of 122 km planned), with 33 stations and 143 buses. It connects the high-density community of Soweto with the central business district and carries 70,000 passengers per day [58].

Cape Town (South Africa) started operations of its BRT in 2011. There are systems in intermediate planning stages in Port Elizabeth and Pretoria (South Africa); Dar es Salaam (Tanzania) and Accra (Ghana) [56]. Other cities considering BRT include Kampala (Uganda), Nairobi (Kenya), and Bloemfontein – Ethekwini, East London – Buffalo City, Ekurhuleni, Polokwane, and Rustenburg (South Africa) [56].

The main challenges for African cities are the creation of local capacity to oversight and operate systems, transforming the paratransit informal services and funding the capital costs (infrastructure and buses) [56].

Future Directions

BRT will evolve in several directions, namely:

1. BRT will gradually become an integral part of most transit systems, as the cities grow their corridors into networks and integrate BRT services with other modes of transport (metro, regional rail, and standard buses). Pedestrian and bicycle access will be improved, and bike- and car-sharing services will be incorporated around BRT stations.
2. Automatic guidance systems, using video, magnetic or physical devices, will evolve to ensure optimal docking at stations. In some cases, priority lanes will be intermittent; only a few meters ahead and behind the bus will be reserved using advanced signal and communications technologies, at other times the lanes may be used for general traffic [59]. This will eliminate the perception of "empty lane" in systems with headways beyond 2 min.
3. The buses will have several advanced technology components: hybrid buses, plug-in hybrids, or fully electric with high autonomy or extra-fast battery charging systems at each station. Alternative technologies will evolve, such as solar recharging hydrogen fuel cell, biofuels from sustainable feedstock, among others.
4. Programming and operations will improve due to the availability of intelligent transport systems (ITS), including the integration into the signal networks (advanced transit signal priority [TSP]). Improved control (Global Positioning System [GPS], Automatic Vehicle Location [AVL], and Operations Support Systems) will allow optimal regulation and dynamic equilibrium of the supply (buses) and the travel demand (passengers). Very advanced routing systems will be possible, including super express, express, and local, services, as well as direct services, to reduce transfers.
5. Fare collection systems will be integrated into cell phones and turnstiles will no longer be required. Tickets will be deducted automatically from electronic wallets, which will have other multiple applications, just as debit cards. User fares will be differentiated by time of day, day of week, and length according to the supply and demand conditions of the system, increasing efficiency and service quality.
6. User information systems will be dynamic, with electronic panels that indicate the next bus and public announcements, helping users to navigate the system in advanced screens or cell phones.

7. Land use along the corridors will include good accessibility, high-density, and mixed uses (Transit-Oriented Development [TOD]). BRT will support urban development and vice versa.
8. Contracts with private operators will be based on performance, with dynamic adjustment formulas of their revenue according to changes in input costs.
9. Infrastructure, technology, training, education, and control will ensure safety, with a vision of zero tolerance of severe injuries and fatalities.
10. BRT will facilitate physical activity, low or zero emissions, and universal accessibility (disabled people).

Many of these advances are already applied in several systems around the globe or under research and development. Integration into future BRT systems will happen in the next few years.

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Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects

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Article Outline

Glossary

Access time The component of door-to-door travel time spent leaving the point of trip origin to a transit stop.

Annualized operating cost The direct cost of operating and maintaining a transit route or set of routes over a whole year; an average value.

Articulated bus A bus vehicle with three (exceptionally four) axles and two (exceptionally three) body sections connected by body joints that provide a continuous interior for passengers. Body articulations allow the bus to make turns occupying a moderately wider body profile than a regular, two-axle bus.

At-grade BRT Bus rapid transit that is predominantly on ROW B and has most of the following elements: signal priority at intersections and other preferential treatments elsewhere; well-spaced stops like stations, with good passenger amenities; regular, reliable services throughout the day; off-board fare collection; real-time arrival information; large, distinctive buses allowing rapid passenger exchange; and a clear, branded image.

Automated guided transit (AGT) Automated vehicles, operated on ROW A, in either a shuttle or loop configuration, typically serving internal circulation needs of large institutions or downtowns. Vehicles may be either steel wheel or rubber tired.

Average operating speed A performance indicator computed by dividing the length of a route or line by the travel time required.

Bogie or truck (United States) Frame containing axle, motor, and brake assemblies and pivots under the body/chassis of a rail vehicle.

Build-operate-transfer (BOT) A project implementation method where one single entity is responsible for building transit infrastructure, procuring all needed equipment and managing the operations for an initial period time before the eventual handover to public ownership.

Bus lane Traffic lane for exclusive (or dominant) use by buses. It may be:

Contraflow – Operating in the opposite direction from other traffic.

Exclusive – Physically separated lanes (usually two) for bus use only.

High Occupancy Vehicle (HOV) Lane – A traffic lane open only to vehicles with more than a minimum number of persons onboard.

Regular – Lane on urban street or motorway reserved only for buses, separated by markings, signs, or cones but not physically separated.

Bus rapid transit (BRT) or bus transit with high level of service (BHLS) Bus transit system with mostly ROW B, long spacings between stops, signal priorities, vehicles with distinct image, and other rail-like components for high performance.

Bus transit system (BTS) A bus service designed as a coordinated system with average stop spacings of at least 300 m, some bus lanes, passenger-friendly vehicle design, operations control, passenger information, etc., for higher speed, reliability, and efficiency.

Consist A set of rail vehicles coupled into a train.

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Cross-subsidization The concept of using excess revenues (profits) from one line or route and using them to support another line that earns revenues less than its costs.

Deadheading Moving a transit unit to a line from a depot or storage location or repositioning a vehicle to another line without passengers.

Design-build model An approach to major projects making the same firm/consortium responsible for both the design and construction phases.

Design-build-operate-maintain (DBOM) model An approach to major projects in which the same firm/consortium is responsible for the design, construction, operation, and maintenance phases.

Diametrical line (or route) A transit line that has a radial alignment from a suburb to center city, crosses it, and continues into another suburb.

Economy of scale The unit cost of output decreases with the quantity of output.

Elasticity of demand The percentage change in ridership over the percentage change in some other quantity (e.g., fare or frequency)

Frequency The rate at which transit units pass a fixed point, usually expressed per hour; it is the inverse of headway but usually expressed in minutes.

Global positioning system (GPS) The currently dominant vehicle location system, based on taking position fixes from multiple satellites.

Guideway A travel way (rail track, guide beam, and other guiding surfaces) that physically guide vehicles. Guideways for nonrail vehicles always require ROW A.

Headway The time interval between transit units passing a fixed point, usually expressed in minutes. It is the inverse of frequency, which is usually expressed as departures per hour.

High occupancy vehicle (HOV) lane A traffic lane open only to vehicles with more than a minimum number of persons onboard.

Hybrid vehicle A bus or rail transit vehicle that combines two different forms of propulsion like an internal combustion engine and an electric motor, which operate in optimum combination for each regime, such as in acceleration, low or high speed, etc.

Intelligent transportation system (ITS) A package of hardware and software specifically designed for improving transportation operations, information to the public, and/or information for service planning.

Interlining The practice of having a vehicle continue onto another line or route rather than reversing at a terminus.

Level of service (LOS) The combined service characteristics experienced by the user.

Light rail transit (LRT) A transit mode utilizing predominantly ROW B, sometimes A or C, on different network sections. Its electrically powered vehicles operate in one- to four-car transit units. The mode has a wide range of LOS and performance characteristics.

Light rail vehicle (LRV) An electric rail transit vehicle, powered or unpowered, with up to seven body sections and overall length of 20–50 m capable of operating on ROW A, B, and C.

Line capacity The maximum throughput of transit units (TUs) or spaces measured at one point on a line on a per-unit time basis; it has a wide range of values depending upon safety regime and assumed crowding standards.

Linked trip A trip that includes all segments a user makes on public transport vehicles.

Load factor or coefficient of utilization Ratio of passengers in a vehicle/transit unit and its total capacity in spaces.

Locally preferred alternative The project alternative selected locally that is then submitted to the federal government for further review and a funding decision (specific to the United States).

Marginal cost The cost to carry one more vehicle on a roadway, one more person in a transit vehicle, or, in general, the cost of providing one more unit of service output.

Maximum load section (MLS) The segment of a line or route on which the maximum number of passengers is carried.

Metropolitan planning organization (MPO) A governmental body legally required to do transportation forecasting and to propose a transportation improvement/investment plan for a metropolitan region (specific to the United States).

Modal split The fraction of trips by a particular mode along a route or line, between two points, or across an entire region.

Monorail An urban transit technology that operates exclusively on right-of-way A using in most cases tires for both lateral and vertical support on a beam with a special cross section, typically a proprietary design.

National Transit Database (NTD) A source of operating statistics and cost information for each transit agency receiving federal funds that is broken into categories used for cost modeling and estimating (United States only).

No-build scenario A project alternative used to compare what may happen if no action is taken. The no-build alternative may sometimes include modest Transportation Systems Management investments.

O-Bahn Bus transit technology in which buses have two horizontal wheels and roadway has two lateral surfaces; the buses can operate on regular streets or enter sections where guiding wheels stretch out and provide guidance against the lateral surfaces so that the driver does not steer.

Operating speed Average speed on a line or network including times for stops, but not terminal times and deadheading.

Opportunity cost The forgone possibilities when resources are committed to a particular project alternative.

Pantograph A spring-loaded mechanism mounted atop electric vehicles that glides along and collects current from a suspended high-voltage catenary.

Paratransit In the narrow definition, services provided as a public service on a demand-responsive basis; in the broader definition any for-hire services that are not fixed route (e.g., taxis, jitneys, vanpools, airport shuttles, etc.).

People mover The informal name for Automated Guided Transit (AGT) system.

Public–private partnership (PPP) A method of project development in which responsibilities and finances are divided amongst various parties in recognition of the benefits each can receive, hopefully to the mutual benefit of all parties.

Radial line (or route) A line or route that begins in CBD or at a center of activity and goes to suburbs, in the direction of lower demand density.

Real-time passenger information (RTPI) The estimated arrival time for a vehicle at a particular stop based on tracking of actual location versus scheduled location; it can be delivered with signs in the field over the Internet, over Personal Digital Assistants (PDAs), cell phones, etc.

Regular Lane on urban street or motorway reserved only for buses, separated by markings, signs, or cones but not physically separated.

Right-of-way (ROW) Broadly speaking, any path or way on which a transit vehicle travels. Transit rights-of-way (ROW) are classified in three categories:

Category A Right-of-Way (ROW A) – Fully controlled ROW without (or with fully protected) grade crossings or any legal access by other vehicles or persons; also called "grade-separated" or "exclusive" ROW. It can be a tunnel, aerial, or at-grade level.

Category B Right-of-Way (ROW B) – ROW horizontally separated from other traffic (by curbs, barriers, grade-separations, etc.), but with grade crossings for vehicles and pedestrians usually at regular street intersections.

Category C Right-of-Way (ROW C) – Surface streets with mixed traffic. Transit may have preferential treatment, such as reserved lane but not physically separated lanes, or it may travel in general traffic lanes.

Short turning Transit line on which some transit units turn back at a station closer than the outlying terminal.

Shuttle A route that consists of only two stops, one at each terminus.

Space-averaged load factor A performance indicator used to measure vehicle space consumption efficiency over the length of a route, computed as the ratio of total space-distance consumed over total space-distance offered.

Streetcar A rail transit mode consisting of electrically powered rail vehicles operating in one- to three-car transit units, usually on ROW B or C.

Sustainable Development The concept that economic development should take place so that nonrenewable resources are not depleted and natural systems of restoration and pollution mitigation are not overloaded.

Tangential route (or Line) A route or line that does not enter into a central area, but instead connects peripheral locations, generally having the

property of more even loading because demand does not increase continually as with radial routes.

Timed-transfer system (TTS) A network consisting of transit lines and one or several transit centers or focal points at which transit units from intersecting lines arrive simultaneously, allowing easy passenger transfer in all directions.

Tramway See Streetcar

Transit signal priority (TSP) The control of traffic signal timing, and possibly street layout, designed to favor transit vehicles over private vehicles.

Truck See Bogie

Unlinked trip A trip counted separately, even if it may actually be a transfer between two transit vehicles.

Zonal service Transit service in which trains operate express or local along different sections of the route, with connections between zones only at a few joint stations.

Definition of the Subject

The term "urban public transit" encompasses a family of modes each serving a particular transport market. These modes can be arrayed by their costs and the quality of service they provide. Toward one end of the spectrum is the typical urban bus mode. At the other end are the regional rail systems with their high speeds and high capacities. In between, urban transit modes have ranges of cost and performance that overlap, and choosing between them may be difficult. Over the last several decades, the modes most often seen as competing for selection are bus rapid transit (BRT) and light rail transit (LRT).

This debate between the BRT and LRT advocates has too often been destructive, pitting two important urban transit modes against each other when the real "enemy" is the overuse and overfunding of the private car. Policymakers are often left more confused as they listen to the different opinions of their transit advisors. Sometimes they are led to believe that they will be able to save money with BRT yet get the same level of transit service and capacity as with LRT; in other cases they realize that an LRT solution is the better one even if it requires higher investment because of its stronger passenger attraction, permanence, and stronger positive impacts on the city.

What would be useful is to understand why and how the BRT and LRT modes evolved and what roles they play within a public transit network. Important in this context is to see BRT as several distinct services, each important, but few providing the speed and capacity of light rail transit.

Introduction

There has long been an ongoing debate in urban transportation on the role of bus and rail modes in urban transportation. That debate is actually a "subproblem" of the overall urban transportation problem – the relationship between public transit, private cars, pedestrians, and other modes. This problem occurs in all countries when auto ownership increases rapidly. The debate eventually defines the main issue: medium and large cities face the "collision of cities and cars." The excessive traffic congestion caused by cars, which is wasteful, environmentally damaging and degrading to a city's livability, can be solved either by extensive construction of highways and parking facilities or by controlling the use of private cars and offering competitive transit systems.

The policies of "adjusting cities to cars" were particularly strong in the United States. From 1945 to 1970, there was massive financial support for highway construction with negligible support for transit and the total neglect of pedestrians.

This wave of "auto mobilization" of cities also encompassed transit planning. A campaign swept the country against rail modes and for the replacement of streetcars by "flexible buses" in mixed traffic. This campaign, fueled by highway, car manufacturers, and the oil industry, also actively worked against rail rapid transit systems. A major consulting firm developed an all-bus plan for Washington, D.C., a city that obviously needed rapid transit. The plan showed buses in huge underground stations with insufficient capacity, lack of signalization, and unacceptable exhaust gases. Moreover, the system would have required higher investment and operating costs than the rail. There was even a campaign alleging that "flexible" paratransit was more efficient for car-based cities than "fixed" rail transit.

Yet, even as the construction of metro and light rail transit lines intensified in dozens of cities in North

America and around the world over the last 4 decades, extreme anti-rail transit views continue in some countries. In the United States, through the 1950–1970 period, the only urban transit modes to choose from were low-investment buses and trams (streetcars), and very high-investment rail rapid transit (metros or subways). The evolution of the tram into light rail transit (LRT), first introduced in Europe in the 1960s and then in the United States by 1980, gave urban planners a rail mode with some of the attributes of rapid transit that was more cost-effective in medium-density corridors and medium-size cities. This evolution was made possible by relocating trams from city streets and mixed traffic onto their own, separated (generally) at-grade rights-of-way.

Over the last 2 decades, a similar evolution has occurred with buses. Early on freeway bus lanes were introduced. Later, select bus routes on urban streets were upgraded through a series of smaller steps including longer bus stop spacing and preferential lane and signal treatments. As the ultimate step in this evolution, several cities have built largely grade-separated busways (e.g., Ottawa and Bogotá). This wide range of bus improvements was given the single label bus rapid transit (BRT) (Fig. 1).

However, the introduction of the BRT concept has again ignited a campaign that BRT can provide the same service as rail transit but at a much lower cost. As further discussion will show, BRT offers a different set of features than rail transit and it differs considerably from LRT, so that services of the two modes are by no means fully comparable. Nor are their permanence and impact on cities comparable.

The debate between BRT and LRT advocates is important because policymakers who want to improve their transit systems often do not understand what each mode is able to deliver. The ongoing arguments among their advisors on the merits of BRT versus LRT are destructive for two reasons: they waste time and too often further delay already long-delayed decisions, and they play into the hands of those who are against any improvements to public transit.

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 1
Two BRT vehicles in Bogota, Colombia can carry all the people in the cars shown in six highway lanes

This section reviews the evolution of both LRT and BRT and explains how each might meet the transit needs of cities. It defines the subcategories of bus services that fall under the umbrella term "BRT" in an effort to separate bus systems which have many LRT features (primarily separated ROW B, signal priority, and long lengths between stops) from buses which have only a few operational improvements.

Process and Controversies in Selecting Transit Modes

Civic leaders, transportation planners, and the public in general are increasingly recognizing that urban transportation policies, specifically the selection of transit modes, have a major impact on the type and quality of transportation, as well as on the entire city's character and quality of life.

Selection of transit modes is therefore a major step in urban transportation planning. Many factors that should be considered in comparing and selecting transit modes can be grouped into several categories:

- *System performance*: transporting capacity, speed, reliability, safety, comfort, and other elements.
- *Economic aspects*: investment and operating costs estimated for the projected quality of service, volume of attracted passengers, and applied fares.
- *Direct and indirect impacts*: The effects of the planned transit system on the area it serves and the entire city.
- *Role of transit on the livability, sustainability, and global impacts on weather change, energy consumption, and other broad aspects*: The planned transit line or network must analyze these long-term aspects, which are gaining increasing importance.
- *Quality and permanence*: Numerous other factors, such as the ability to protect the transit right-of-way from use by other vehicles.
- *Local preference*: The preference of the population for different transit modes.
- *Influences by different lobbies*: Groups (e.g., labor unions, business interests), often driven by financial interests rather than public interest, often wish to influence major transit decisions.

To compare transit modes systematically, it is very helpful to consider the elements that define modes. They are:

- *ROW category*: There are three types of ROW: A (fully grade separated), B (separated from other traffic), and C (within mixed traffic).
- *Technology*: Its main components are support (road or rail), guidance (steered or guided), propulsion (diesel or electric), and method of driving and control (manual or signalized).
- *Type of service*: This characteristic includes line length and functional role (short-haul, regular city service or regional).

While planning and attention to mode selection must be performed carefully, excessive controversies can be very harmful because they often cause long delays and lead to incorrect decisions, such as selection of a mode without sufficient capacity, with an inferior ability to attract passengers, or a mode that is later degraded by a failure to protect its ROW.

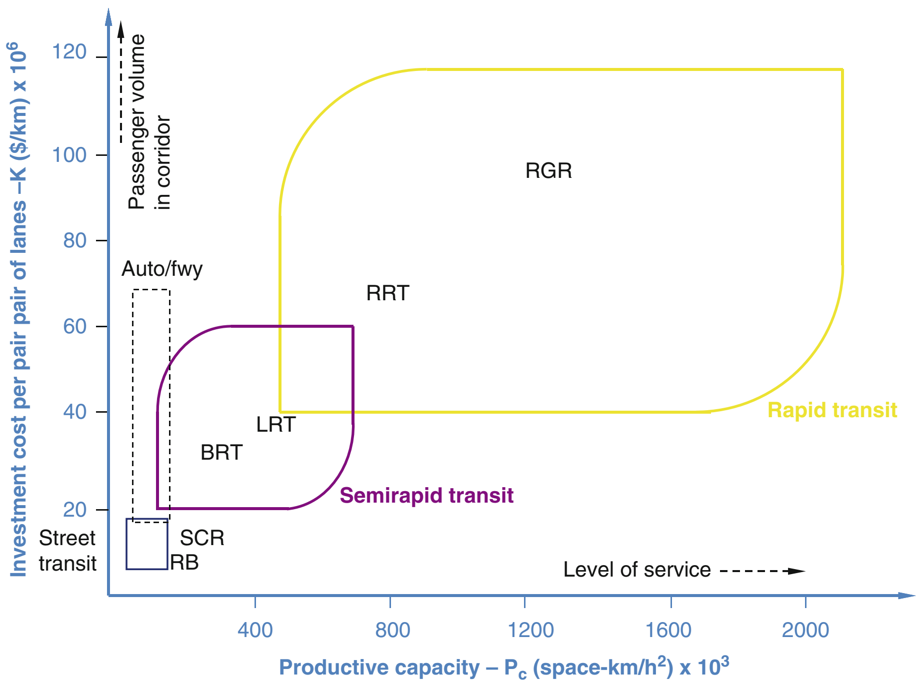
The "family of transit modes" can be formed by listing the modes from the lowest capacity minibuses on ROW C through medium-capacity modes on ROW B, including BRT and LRT, and AGT, metros and regional rail systems with long trains on ROW A providing the highest capacity and performance. When the average investment of these modes per kilometer of line is plotted on the ordinate, the diagram of the family of modes in Fig. 2 shows three areas with their increasing performance and investment costs.

Negative Trends in the Application of Urban Transit Modes Between 1945 and 1975

This entry discusses many of the factors that led to the creation of the distinct BRT and LRT modes.

Impact of Auto-highway Expansion on Selection of Transit Modes

Public transport companies, facing heavily subsidized highway construction for private vehicles and virtually no public assistance for transit investments and operations, were forced to convert their systems from electric streetcars and trolleybuses to motorbuses. Part of this conversion was logical when diesel



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 2
Relationship between system performance (productive capacities) and investment cost of different generic classes of transit modes

buses were upgraded so that they became more economical and required less investment than streetcars on lightly traveled lines. However, conversion of heavily traveled streetcar lines, particularly those which had separated rights-of-way (category B), was made with explanations that streetcars were obsolete, buses were "more flexible" to mix with general traffic, their lines could be easily changed, etc. Such conversions were mistakes that led to downgrading of transit services in general.

If urban transportation is analyzed as a multimodal system, the nearly complete conversion of streetcars/tramways that was done in the United States, United Kingdom, France, and a number of other countries, had the following results:

+ Lower investment cost for line infrastructure (tracks and overhead cables)
– Loss of transit ROW B and the operation of "flexible" transit vehicles in general traffic, which resulted in reduced speed, reliability, and loss of distinct image of transit services
– Change from rail to bus vehicles which are smaller, less comfortable, have fewer doors, and cannot be coupled in trains (lower line capacity)
– Change from electric to diesel traction, which downgrades performance, generates exhaust gases and noise, and prevents operation in tunnels

Downgrading of Transit Services

There were secondary impacts of the conversion from rail to bus transit. In many cities conversion to buses was followed by the belief that "flexibility" of buses should be used to replace a single heavily traveled line with high frequency of service by a large number of bus routes that provide better area coverage but have longer headways, lower speed, and reliability of service. Such extensive networks, which still exist in many cities, require less transferring, but offer services that have long headways and irregular alignments, resulting in low recognition and image. The belief was that copying services private cars offer would increase transit ridership. However, the opposite happened. Extensive

networks of bus services with long and irregular headways attracted significantly fewer passengers than a smaller number of streetcar lines with frequent services.

Replacement of Streetcars by Buses Led to Major Losses of Passengers

The substitution of networks of rail lines having frequent, fast, and reliable services with extensive networks of infrequent bus services was not only less attractive, but in the long run its lower image and permanence diminished the role of transit and made it supplementary to private cars, particularly in small- and medium-sized cities. This was demonstrated by the fact that the number of passengers carried by buses in US cities consistently decreased even during the period between 1950 and 1970, when buses were introduced in many cities to replace streetcars.

Decreasing transit ridership, increasing traffic congestion and deterioration of cities led many cities to search for higher quality of transit services. The experience with "flexible" buses led to realization that making transit vehicles independent of general traffic is the basic element in achieving transit competitive with private cars.

Many cities tried to introduce reserved bus lanes, but found little support from traffic engineers, and great difficulties getting the police to enforce lane separation. The concept of LRT with tracks physically separated from other traffic by curbs was a logical solution to this problem, and since the late 1970s, about 20 cities in North America have introduced LRT systems with separated and protected ROW on their main lines. With the introduction of rail vehicles with greater comfort, more space, and higher speed than buses, many cities were very successful in reversing downward trend of transit ridership.

Two Major Trends in Transit Role Definition and Mode Selection: "Flexible Buses" or Upgrading Streetcars into LRT

Between the 1950s and the 1970s, policies on the selection of transit modes varied among cities depending on local conditions, methods of decision-making, financing sources, and the expertise of transportation planners and transit agencies. Nevertheless, a review of trends during this period of rapid car ownership increase in North America and Europe showed two distinctly different major groups of cities.

Cities with Policies That Encouraged Automobile Use: These policies facilitated unlimited private car use. They were followed in most US, UK, French, and Spanish cities, and they resulted in massive replacements of streetcars/tramways by buses in mixed traffic as well as extensive construction of freeways in urbanized areas. Metro was considered the only alternative for high-performance transit competitive with private cars.

Cities with Policies That Fostered Balanced Intermodal Transportation: These policies implemented *parallel improvements* of streets/highways and transit systems to achieve a balanced urban transportation system. They were the basic transportation policies in most cities in Germany, Switzerland, Austria, Benelux, and most Scandinavian countries as the only solution leading to livable cities. The main element in achieving transit competitive with private cars was recognized to be physical separation of transit, that is, the provision of ROW B and A. Selection of these separated ROWs made LRT the logical choice, because rail offers significantly higher performance, comfort, and image in the city, as well as greater permanence of transit ROW. These advantages were given more weight as, since the 1970s, most busways in the United States were downgraded into HOV facilities, greatly diminishing the priority of buses over other types of vehicles (Fig. 3).

The results of the two sets of urban transportation policies were drastically different with respect to mode selection as well as livability of cities. The cities which followed balanced transportation policies systematically upgraded tramways and buses on streets into semi-rapid transit modes to counter the increasing attraction of private cars, and to make transit independent of traffic congestion. The cities attempting to accommodate the increasing volumes of auto traffic found themselves with low-quality transit buses in ROW C facilities and with an inability to build extensive metro networks due to its high investment cost. Eventually, many of these cities realized that they needed transit modes that offer much higher performance than do buses on streets, but at significantly lower investment costs than metro systems. The LRT

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 3
Initially an exclusive bus roadway, the El Monte Busway in Los Angeles, USA has been degraded into an HOV facility, even allowing single driver hybrid cars

mode met this requirement, and it has been built in dozens of cities in the United States, France, United Kingdom, Spain, Canada, and others. Later development of the BRT mode provided another opportunity for these cities to build medium-capacity modes, narrowing the "gap" between buses on streets and metro systems.

Inherent Differences Between Industrialized and Developing Countries

What follows is a generalization. There are, of course, wide differences between particular nations, and even cities within the same nation. Moreover, some economies have such rapid development that the context for planning transport is continually changing. While rapid change increases the need for dramatic action, it also increases the risk of unforeseen consequences from implementing a project. The following are conditions that make the selection of modes in developing countries different than their selection in industrialized countries.

Demographics: Richer countries, by definition, have a population with more travel mode and destination choices. Thus, most new public transportation enhancements in such countries must pay heed to the needs and desires of so-called "choice" riders. While the fare levels are not unimportant, they are less important than creating attractiveness for persons who can afford the high investment and operating costs of auto ownership.

By contrast, in developing countries a large percentage of the population is "captive" riders. They will be either walking or using public transportation. They are much more sensitive to the fare level. If the fare level can be kept very low by allowing greater crowding, this option is often employed even at the expense of losing many choice riders.

In rapidly developing countries there is a need for public transport investments that address both choice and captive riders. On the one hand, suppressing auto use by affluent persons becomes an important goal. On the other hand, an increasing population of lower and medium-income persons and higher development densities demands a goal of providing high capacities

with moderate fares. The question then arises whether one mode can address both goals simultaneously or whether different systems must be built for different passenger segments.

Wage levels: Public transport systems in the developed world typically use 70–80% of their operating budget for salaries, wages, and fringe benefits. Thus, it becomes of vital importance to identify and employ technologies that increase worker productivity. Some well-capitalized public transport systems have seen continuing increases in service output with little increase in staff size. The ability to increase consist size without additional drivers is one of the main reasons for upgrading high-demand bus corridors to rail modes. Furthermore, state-of-the-art self-service fare collection like pay-by-phone, computer-aided dispatching for field supervision, Internet-based itinerary planning services, and other advanced technologies can pay for themselves. The ultimate productivity gain is conversion of rail lines to full automation to remove the driver.

By comparison, well-organized transit agencies in developing countries often pay a small fraction of the hourly labor rate paid in richer countries, and with fewer benefits. At the same time, funds to purchase advanced technologies are likely to be scarce. In such an environment, the case to go to rail technologies, or even to larger buses, is not as compelling.

Employment policies and labor regulation: In many developing countries, governments view public transport as a significant source of employment. In some cases, publicly owned services are overstaffed. In many more cases, the vast majority of transport services are provided by owner-operators or persons renting or leasing vehicles from owners of bus fleets. In such situations, attempts to build public transport networks on high-capacity corridors using very large vehicles often meet strong opposition. A recent and dramatic case is the entirety of South Africa. Efforts to design BRT networks in Gauteng (Johannesburg-Pretoria), Cape Town, and Nelson Mandela Bay all met intense, and even violent, opposition from minibus syndicates.

While it may be logical to suggest that the mobility of millions of persons is more important than the employment of a few thousand persons, it is a fact that politicians can be very wary of labor opposition, particularly in the context of high unemployment. In such cases, the higher labor productivity of rail or large BRT buses is not a particularly strong selling point. (Actually, rail systems do have a lot of other employment in track, station, and vehicle maintenance.)

Financing capacity: The ability to finance major construction projects can be a problem for many cities even in the richer countries. For many poorer cities and countries, it means increasing taxes or depending upon international investment banks that attach conditions to their grants and loans. Either option can be unattractive to politicians.

One of the consequences of the difficulty to finance transit projects is the controversy between building BRT and metros. This is true even for very large cities that need the capacity of a metro due to large populations, long travel distances, and severe street congestion. The choice in such cases is often between the lower investment costs per kilometer of lower-performance BRT, or the higher investment for a higher performance and more permanent rail system.

Organizational capacity and effectiveness: In many developing countries, the existing institutions at the city, regional, and/or national level do not have the ability to design, build, or manage modern high-capacity public transport systems. This lack of capability acts as a deterrent to even consider many projects. One case is instructive. A need for a metro network in Delhi was recognized in 1997, but neither the national government nor prospective international lenders believed that the existing public agency could design, build, or manage such a system given its record of gross overstaffing and inefficiency. Thus a new corporation to be headed by a proven manager was created. In the end, the corporation not only built an excellent metro rail system, but it was well poised to compete against international firms for future projects in other Indian cities.

Public participation: Most of the industrialized countries have public participation laws designed to allow affected parties as well as the average citizens to influence the design process. These laws are a democratic response to cases where citizens receive a new transportation project that they would not have selected had there been more input. This process slows down the design effort, but it also

presumably results in a more beneficial and just project in the long run.

Many developing countries, even with well-intentional planners, do not have formal public participation processes. Thus, planners must design systems with less knowledge of the needs and desires of potential users. The technical expertise of planners and engineers is therefore of primary importance.

On the other hand, in some developing countries governments have greater powers than in democratic industrialized countries. This can make the design and build steps far easier, quicker, and more efficient.

Right-of-way acquisition: Obtaining reserved ROW B is the basic element determining the feasibility of semi-rapid transit, BRT or LRT. The possibility of getting a protected ROW depends on many factors, often different in developing and industrialized countries. Advocates of BRT claim that 8–10 m strips of land can be obtained easily in many developing countries because auto traffic volumes are lower than in industrialized countries. However, in numerous cases the expected acquisition of such rights-of-way has proven to be unrealistic.

The reasons for this discrepancy of theoretical claims and real-world implementation are many. Although car ownership in those countries is still low, street traffic congestion is often even more acute than in industrialized countries because their streets are even more congested by trucks, minibuses, rickshaws, taxis, bicycles, pedestrians, and other participants. The diversity of modes makes traffic conditions even more chaotic and difficult to regulate. This makes acquisition of protected traffic lanes extremely difficult. For example, in several cities, fleets of buses that were bought for planned BRT systems had to be stored in expectation that the BRT infrastructure will be built later. In Jakarta, there were legal challenges of exclusion of other traffic from bus lanes, while in New Delhi regulations allowing and prohibiting taxis from BRT lanes was changed several times.

In industrialized countries there is also a major difference between BRT systems in theory and in practice, but for different reasons. A number of successful reserved busways with most BRT elements were downgraded by their conversion to high occupancy vehicle (HOV) lanes. The decisions for these changes were made by judges in courts (discontinuance of HOV lanes on the Santa Monica Freeway in Los Angeles), by city councils (discontinuance of a bus mall in Philadelphia), by state legislatures (conversion of the El Monte Busway in Los Angeles to HOV lanes), and by other bodies which have no professional expertise in urban transportation.

Decisions to retain the exclusive use of busways by buses or to allow other vehicles vary among cities and countries. In the United States, many exclusive busways have been downgraded to HOV facilities, in many cities taxis are allowed to share busways, and most recently hybrid passenger cars are given this privilege. In Madrid, motorcycles are permitted in busways.

Modal integration: In the more developed countries, it is common for one agency to either provide all services, regardless of mode, or else manage them under one coordinated fare structure. The operator of a particular vehicle in no way depends upon the fares collected (or not) from boarding passengers. In such an environment, it is possible to institute significant or even total network reorganization with the advent of a new mode. Thus the lower income person is not unduly penalized for needing to transfer between services.

By contrast, most developing countries have cash-based operators that depend on retaining all or part of the money collected. At the same time, riders are forced to pay a full fare each time they switch between vehicles or modes. Thus, both the operators and riders have reason to oppose the imposition of a new higher-capacity mode within their existing network. The former sees a revenue loss and the latter sees paying additional fares to use the new service.

Traffic enforcement: Police control and enforcement of exclusive transit rights-of-way is very different for the two semi-rapid transit systems. LRT requires very little police control, mostly limited to intersections. A BRT lane, when it is immediately adjacent to other traffic lanes, is always attractive to road vehicles traveling in other lanes, so that police enforcement must always exist at intersections and bus lanes between intersections.

Police enforcement depends on local police effectiveness, which varies among cities. For example, cities like Singapore and New York have stricter controls than

Boston and Moscow. Similar variations exist among cities in developing countries, but in many of their cities the practice of bribing policemen degrades the traffic discipline even more.

Light Rail Transit

Cities which adopted policies of implementing balanced transportation concentrated on upgrading transit by developing rail transit networks on ROW categories B and A. This has been the most important measure making transit independent of street traffic congestion and therefore competitive with the private automobile. Transit on exclusive ROW logically led to the development of advanced articulated rail vehicles, increased operating speeds, reliability, comfort, and safety.

Major changes in medium-capacity rail transit, most of which took place in Germany, The Netherlands, Belgium, and several other European countries, created a transit mode that is actually more similar in its performance and efficiency to metro/rapid transit than to conventional streetcars/tramways, so that it was given a new name: light rail transit, LRT, or Stadtbahn in German (Figs. 4–6).

Development of LRT Mode

Following several decades of system design, rights-of-way development, and technical and operational innovations, LRT has become a very diversified mode. The most significant innovations that led to the creation of LRT and its introduction in dozens of cities are listed in the box below.

It is interesting to note that during the 1970s and 1980s many cities built tunnels for center-city sections of LRT to make their operations as close to the metro as possible. This was the case, for example, in Frankfurt, Stuttgart, Edmonton, and Hannover. Since 1990, however, an increasing number of cities have designed LRT systems that run through pedestrian zones with decreased or eliminated general traffic. For example, in cities like Strasbourg, Calgary, Denver, Barcelona, and Istanbul, LRT trains travel through central cities at lower speeds than tunnels would allow, but that often does not result in longer passenger trips because it eliminates for passengers the time and effort of walking two levels into and out of underground stations (Fig. 7). Heavily traveled lines with longer trips and a need for higher speed are, however, still being placed in tunnels, on aerial structures or other types of

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 4
Tramway on ROW category C in Milan, Italy

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 5
LRT on ROW category B in Paris, France

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 6
LRT on aerial structure in Los Angeles, USA

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 7
LRT within a pedestrian zone in Karlsruhe, Germany

exclusive ROW, as is the case in Dallas (Fig. 8), Cologne, Copenhagen, St. Louis and Rouen.

Major Steps in the Development of LRT and Its Role as the Leading Medium-Capacity Transit Mode

- Consolidation of extensive tramway networks into fewer, high-performance LRT lines.
- Systematic replacement of ROW C (street running) by ROW B and A, that is, separated ROW.
- Use of street medians, tunnels, or aerial alignments on the same lines.
- Intermodal integration with bus and metro lines through construction of joint transfer stations.
- Development of high-quality rails and switches that provide quiet and virtually perfect riding comfort, far superior to buses and rubber-tired AGT systems.
- Articulated vehicles offering spacious comfort, operated as one- to four-car trains up to 90 m long with capacities as high as 750 spaces.
- Change from unidirectional tramway-type to bidirectional metro-type rolling stock.
- Self-service fare collection allowing rapid boarding/alighting of passengers on all doors and use of any type of fare.
- Low-floor (0.25–0.35 m above top of rails) vehicles facilitate boarding/alighting of all passengers and meet the needs of the disabled.
- Because of increased TU capacity, one-person crews, and increased operating speeds, the productivity of operating personnel (expressed as passenger-km/h/driver) has increased about 20 times from tramways. Productivity is also about five times greater than on the highest capacity BRT (750 vs 150 spaces per driver, not considering typically higher operating speeds of LRT than BRT).
- Operation of LRT in central cities is performed effectively in tunnels, or, in many cities, by running directly in pedestrian malls and zones (with lower operating speeds on such sections).
- Integration (track sharing) of LRT with regional rail lines for services to suburbs and nearby cities.

Major Types of LRT Applications

Successful construction of LRT in many European cities led to numerous professional conferences and the adoption of LRT as the leading medium-capacity transit mode in many countries which had eliminated streetcars/tramways during the 1950–1970 era: United

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 8
High-capacity high-speed LRT train in Dallas, USA

States, Canada, France, United Kingdom, Spain, and a number of others. During this new wave of building LRT since the 1970s, about 100 cities have either expanded or built new lines and networks. In many cities one or several new LRT lines have become the main transit system carriers with significant increases in transit ridership. This was the case, for example, in San Diego, Calgary, Sacramento, Portland, Strasbourg, Bordeaux, Sevilla, Birmingham, Denver, and many others.

The successful introduction of LRT in so many cities of different sizes and characters is largely due to the extreme diversity of characteristics of the LRT mode. An analysis of the present broad family of tramway/LRT modes has defined ten categories of this mode by its physical, operational features and role it plays in the city's transportation. They are listed in the box below.

Ten Categories of LRT and Its "Neighbors": Tramways and Mini-metro Modes

1. Conventional tramway mostly with ROW B and C: Melbourne, Moscow, St. Petersburg, Toronto
2. Modernized tramways with signal priority, improved stops, prepaid fares, etc.: Amsterdam, Oslo, Prague, Vienna, Zurich
3. New tramways built in redesigned pedestrian-oriented city centers (some also using historic vehicles as center-city shuttles): Grenoble, New Orleans, Nice, Portland Streetcar
4. LRT developed from upgraded tramways: Berlin, Cologne, Rotterdam, San Francisco, Stuttgart
5. LRT with metro network: Boston, Brussels, Philadelphia
6. LRT systems in suburbs of megacities: Hong Kong (Tuen Mun), London (Croydon), New York (Hudson-Bergen), Paris (lines T1, T2, and T3)
7. New high-performance LRT systems: Birmingham, Calgary, Dallas, Denver, Nantes, Portland, San Diego
8. Light Rail Rapid Transit (LRRT): LRT on ROW A only, also referred to as a "mini-metro": Kuala Lumpur, Manila, Philadelphia (Norristown Line)
9. Automated LRT: same as #8, but fully automated and without driver: Copenhagen, Kuala Lumpur, London (Docklands), New York (JFK Airport), Vancouver (Skytrain)
10. LRT/Regional Rail integrated systems, popularly (although incorrectly) known as "Tram-Train": Bern, Karlsruhe, Kassel, Manchester, Saarbrucken

Review of LRT Characteristics

An analysis of the development and broad deployment of LRT in many cities shows that this transit mode has many characteristics that make it an optimal

solution for cities that need medium-capacity transit systems, that is, those that perform much better than regular buses on streets, but require a substantially lower investment cost than metro systems. Main characteristics of LRT are summarized in the following box.

LRT has several other physical characteristics that distinguish it from road vehicles. First, being a guided system, LRT uses considerably wider and longer vehicles than buses and it can operate in trains. With the high capacity of transit units, LRT can provide a higher line capacity per track than road vehicles can provide per lane. Second, electric propulsion gives LRT systems better performance (acceleration, grade-climbing ability, braking with regeneration of energy), no exhaust or noise along the line, and the ability to operate in tunnels, which vehicles with internal combustion engines do not have. Finally, rail technology makes signalization, automatic train protection (ATO), and other automated safety features possible, so that LRT can operate at higher speeds and at a higher degree of safety than road vehicles.

Positive and Negative Characteristics of Light Rail Transit Compared to Its Peer Medium-Capacity Modes

+ Rail guidance technology has a simple basic mechanism: four to eight wheels per vehicle running on two steel rails.
+ The simplest, fastest, fail-safe switching of all guidance technologies.
+ Steel-wheel-on-steel-rail contact produces extremely low rolling resistance, so that rail modes require the lowest energy consumption per ton of weight of all presently operational transit modes for any given dynamic performance.
+ Rail is the only guidance technology that allows not only at-grade crossings, but also on-street running.
+ Its simplicity and ruggedness give rail technology low maintenance requirements and high durability.
+ It copes better with adverse weather conditions (rain, snow, and ice) than rubber-tired technologies.
+ Modern rail vehicles provide virtually the ultimate in stable, smooth riding comfort.

– Investment cost of rail lines is higher than that for buses, but lower than the cost of other guidance technologies, such as Rubber-Tired Rapid Transit and Maglev.
– The lower adhesion coefficient of steel-on-steel than rubber on dry concrete surfaces gives LRT and other rail modes two relative disadvantages.
– Rail systems cannot negotiate as steep gradients as can rubber-tired systems.
– They must be operated with higher degree of safety because of their longer stopping distance.
– Although modern rail vehicles run extremely quietly on straight sections and mild curves, when negotiating sharp curves, rail vehicles produce more noise and vibration than do rubber-tired vehicles.

Roles and Impacts of Light Rail Transit

The interaction of transit systems with land use planning, physical form, and quality of life in cities is mainly dependent on the infrastructure of the transit system. While transit modes with flexible routings, such as buses on streets, do not have much impact on city planning and form, permanent infrastructure of guided systems provides the certainty that investment decisions require, so that LRT can be used to influence the form and character of a city.

Mayors of several cities which have recently built LRT systems, including Portland, Denver, and Salt Lake City, have often pointed out in their speeches that the introduction of LRT did not only improve transportation services, but it changed the character and increased the livability of their cities as well. Similarly, many cities in France, Spain, Ireland, and other countries have used the construction of new LRT systems as the pivotal project for the reconstruction of entire corridors or central urban areas to make them more pedestrian-oriented rather than car-dominated. Good examples of this are Strasbourg, Lyon, Toulouse, Nice, Dublin, and Valencia (Spain).

Upgrading Bus Services into Bus Transit Systems and Bus Rapid Transit

Local bus routes are the workhorses of the transit industry, and must operate under challenging conditions. They operate in mixed traffic like all other

vehicles. They have no signal priority, and only rarely any reserved bus lanes. They serve many bus stops, often 150–200 m apart, which vary from a small sign on the side of the road to shelters and benches. The driver does fare payment and control at the front door. And local bus routes necessarily serve both short, local trips and long, commuter trips.

Over time, a number of measures that incrementally improve local bus services have been developed and gained increasing acceptance. Taken together, they provide a level of service that has become popularly known as bus rapid transit. Unfortunately, BRT is a term that has been too loosely used to describe too wide a range of bus service enhancements. This has somewhat tarnished the term.

This chapter will first review efforts to make buses act more like light rail within their own guided rights-of-way and within their own tunnels. Concurrently, bus planners began to focus on taking the bus mode and greatly improving its physical and operating environment. The next section will discuss those measures that have given buses preferential treatment in its ongoing struggle with all other vehicles using the streets.

Guided Buses and Buses in Tunnels

In the late 1970s and early 1980s, there were a number of guided busways proposed and a few were built. These efforts were attempts to provide the bus mode some of the attributes of rail transit, or at least make them appear to have the attributes of rail transit: speed, safety, and exclusive, narrow rights-of-way. Other applications used various mechanical arms or wheel assemblies to allow buses to track a raised, guiding curb. Anything raised, of course, made it difficult to move across intersections, and interrupting the contact with the raised curb proved too unsafe. Other designs used electronic or optic sensors to guide the vehicle.

The most lasting of these guided buses was the German O-Bahn concept that was initially built in Essen, Germany, but that test track did not get extended and has been superseded by light rail. An O-Bahn was also built in Adelaide, Australia, and it is still operating there. This concept uses concrete beams with guiding curbs within its own, fully grade-separated right-of-way. This design proved successful to install, if expensive. It has not been replicated elsewhere, except for a few short sections of bus lines (Fig. 9).

Several bus tunnel projects were built to allow buses to avoid surface congestion. The first such project in America was Pittsburgh's original South Busway opened in 1977. It made use of an old tramway tunnel that was converted to serve both buses and light rail trains. There are, however, no stops or stations in the tunnel. The 2.1-km Seattle Bus Tunnel began construction in 1987 and cost $450 M to complete. Operations began in 1990

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 9
Sole major O-Bahn system in Adelaide, Australia

using dual-mode diesel-electric trolleybuses. It became a joint bus and light rail tunnel in 2007. The older buses, which cannot operate with the light rail overhead catenary system, have been replaced with new diesel-electric battery hybrid buses. Thus, tunnels for BRT have cost in some cases more than tunnels for rail modes, including LRT and metro systems.

By far the longest bus tunnel built in North America has been a section of the Silverline near South Station in Boston. The project was poorly conceived and represents an extremely expensive facility with very poor results. This bus tunnel cost about $500 million per mile ($350 million per km) to build. To solve the problem of diesel motor exhaust, dual-mode (diesel/electric) buses have been introduced. The tunnel has curves with limited sight distances, but has no signal protection, so that speed is limited on different sections to 10–20 km/h. At the exit of the tunnel, there is a traffic signal that further delays trolleybuses 1–2 min. The line then continues to the airport, where buses stop along a frequently congested four-lane roadway. Picking up passengers with luggage who have to pay fares on board also slows the service down.

The Silverline in Boston demonstrates that claims that BRT is always much cheaper to build than LRT is not correct. Actually, in many cases (Seattle, Boston) BRT tunnels have involved much higher investment cost and provided much lower system performance than rail tunnels.

The Development of Bus Preferential Treatments

For many decades buses were treated no differently than any other street vehicle. The result was slow service and poor reliability. Gradually, planners began to realize that providing preferential treatment for buses increased transit speeds, attracted riders, and lowered operating costs. These have increasingly been incorporated into street designs, but there is still a reluctance to provide buses with the priority that their higher passenger loads warrant.

Intersections are where a number of improvements can be made. One basic improvement is to allow buses to go through an intersection from a right-hand turn lane where there is often a bus stop. Providing a lead "queue jumping" green signal from this lane or a "bypass" lane through the intersection also reduces travel time.

The separation of buses onto their own lanes provides much more benefit, but this if often quite difficult in a congested city and is done, even now, only rarely. Reserving the curb lanes for buses is the most common approach because bus stops can still be on sidewalks. Bus lanes can also be located in the center of streets. This is usually an expensive proposition, however, because streets may need to be further widened for bus stops, turn lane storage, etc. Contraflow bus lanes take advantage of wide streets or street pairs to carve out the necessary travel way for buses; in the proper place they can be useful.

Finally, buses have begun to be given (by traffic engineers) various levels of traffic signal priority (TSP). TSP for bus transit usually comes in the form of a "green wave", or "green extension/red truncation" which is limited, for example, to less than 10% of the cycle length. While traffic engineers may give signal priority to buses at many intersections along the route, they are rarely given at all intersections.

A higher level of transit signal priority is traffic signal *preemption*. Light rail trains are almost always given traffic signal preemption when operating faster than 35 mph and preemption often comes with crossing gate protection. These gates are justified because the weight, speed, and long stopping distances of trains require stronger protection and allow higher transit speeds than buses.

Express Bus Services

The first step often taken by transit agencies to enhance local bus services is to supplement the route with limited-stop service. Fewer bus stops means shorter travel times for passengers going longer distances. This is especially appealing during peak commuting hours, which is when many limited-stop bus services operate. Reducing bus stops is a prerequisite for all higher levels of bus operations.

Other than fewer stops, however, many of the features of local bus services remain: no preferential treatment, no dedicated bus lanes, onboard fare payment and control, and no special amenities or service branding.

Enhanced Bus Transit Service

These services add further travel time savings to limited-stop bus services. They retain and even reduce the

number of bus stops of limited-stop bus services. They included bus stops with improved shelters and seating, arrival-time message boards, and if possible extended-curb bus stops that remove the time buses lose moving out of, and then back into, the flow of traffic. Special bypass lanes at intersections, lead "queue jumping" green signals, and special turning lanes can help give buses an advantage at busy intersections. Priority signal treatment that gives approaching buses an extended green signal can be a significant travel time improvement. The ultimate improvement is to give the buses their own bus lanes separated from other traffic. However, as noted above, rarely are designated street lanes of any length given over to bus operations.

Bus services with enough of these enhancements are often branded to reflect their special status and service quality. Often newer, articulated, cleaner-energy buses with special paint schemes and catchy names are used to differentiate these services. For example, this network is called Metro Rapid Bus in Los Angeles, Special Bus Services (SBS) in New York, and the Silverline in Boston.

Although these types of services are often given the label BRT, they usually do not include enough enhancements to warrant the label. Enhanced bus services typically lack three key timesaving features: fully separated bus roadways, off-bus fare collection, and traffic signal preemption.

At-Grade Busways

There are at least two major at-grade busways in the United States: the South Miami-Dade Busway and the Los Angeles Orange Line. The Eugene, Oregon's Emerald Express busway may be another, although it does not have the same level of treatment the others do. (Seattle has an approximately 2 km long busway segment south of the bus tunnel.) The first two facilities appear to have all of the ingredients needed to provide service comparable to light rail. They operate over separate bus roadways; they have off-vehicle fare collection; they have traffic signal priority at most intersections they cross; and they have only limited service over city streets. To make up for the inability to trainline buses, these busways use longer, articulated buses to provide more line capacity (Fig. 10).

That being said, the service provided is not comparable to light rail operations. The main reason is that neither the Orange Line nor the South Miami Busway has crossing gates and therefore both must slow to below 32 km/h (20 mph) at each intersection, even with signal priority [1]. The use of crossing gates with at-grade busways has not been allowed by traffic

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 10
The Orange Line BRT in Los Angeles on ROW category B uses articulated buses to increase line capacity

engineers because their operation takes too much green time away from cross traffic [2]. At some intersections the buses on the Orange and South Miami-Dade Busways have no signal priority at all.

Crossing gates are mandatory for LRT above a certain speed typically 55 km/h (35 mph). Because of them, ROW B for LRT can act like a ROW A by providing full protection for the light rail train.

Bus Transit System: BTS

As mentioned above, regular bus services in many cities, including most US cities, are operated very inefficiently: they have stop spacings of 150–300 m (at every intersection), passengers board and alight at any door, colliding with those who are boarding and trying to pay through a single channel door; many buses do not stop close to the curb; there are few bus lanes and nearly no signal priorities at any intersections. Recent efforts to improve such operations have been rather liberally given the term "bus rapid transit." This trend has resulted in downgrading the BRT concept and caused confusion.

This text uses three definitions of bus systems. Regular, conventional (and often inefficient) bus services are referred to as "Regular Bus – RB." Bus services which are improved in station spacings, operations, etc., similar to many bus services in European countries and those in US cities which have been upgraded, are designated here as "Bus Transit System – BTS." Finally, "bus rapid transit – BRT" are the systems which have distinctly higher performance with elements defined rather precisely in the following section.

Bus Rapid Transit

Definition of Bus Rapid Transit There is a consensus [3] that bus rapid transit is a bus system that has the following elements superior to regular bus systems:

1. Reserved (physically separated) lanes or roadway – ROW B or A not shared with other vehicle categories (taxis, HOVs, and others)
2. Distinctive lines with frequent, reliable service and regular headways during all daily hours
3. Distinctive stops with passenger information and protection spaced at least 300–600 m
4. Distinctively designed bus vehicles with large door-to-capacity ratios, low floor, or high platforms
5. Bus preferential treatment at all signalized intersections
6. Use of ITS technology for monitoring vehicle movements, passenger information, and fare collection

However, this definition is rather "idealistic," because there is virtually no bus system in the world that has all these elements. Therefore, it is considered that BRT is a system that has most of these elements.

Several bus systems in the world have achieved an exceptionally high quality and fall in this definition of BRT. Often cited are Bogotá's TransMilenio (Fig. 11), Brisbane's Busways, and Ottawa's Busways. Pittsburgh's Busways could be among them if its image and other elements (station amenities, off-board fare collection) were improved.

The most important requirement for a busway to be comparable to an LRT line is to give it a similar right-of-way and, therefore, a similar operating speed. Because at-grade busway buses will not get the same signal preemption as do light rail trains, greater emphasis – and investment – must be made to give busways more grade-separation at intersections. The need to provide a high level of priority is particularly true in the central business district when a 90 km/h (55 mph) approach on a busway can degenerate into an 15 km/h (9 mph) slog through congested downtown streets. Successful BRT systems try to make this investment (Fig. 12).

BRT stops are also well spaced and more like stations with good weather protection, seating, a sense of security, and real-time bus arrival information. These elements are common with LRT stations, but are too often short-changed on busway lines.

BRT systems use large buses with wide doors for easy and rapid passenger exchange. Articulated buses are common and even double-articulated buses are used. To help market the better BRT service(s), its buses have special bus colors and logos.

BRT systems try to provide BRT buses any preferential treatment necessary through any at-grade intersections or bottlenecks off the ROW A. A number

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 11
Bogotá TransMilenio BRT line

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 12
Bogotá's BRT distribution through central city pedestrian area

of such measures were discussed in the preceding section. It does little good to have great service only on that portion of the bus route that is fully grade-separated if the overall experience of the passenger is mediocre.

BRT systems monitor all aspects of their operation to make sure buses are on time and safe, to provide the traveling public with real-time arrival information and respond to their questions, and to process quickly and efficiently the collection of fares.

BRT systems have robust bus operations with several types of services available. While there is typically the busway-only service equivalent to a light rail line, there may also be express bus services and services typical of a freeway busway with suburban bus routes using the common busway trunk segment. Two things make such a complex operation possible: the design of the busway that allows buses traveling in the same direction to pass each other and the full grade-separation of the busway. This mix of bus operations is beyond the abilities of almost all light rail systems. The extra tracks needed for trains to pass other trains traveling in the same direction are rarely built. Express trains may skip-stop or be scheduled to just catch up with a local train ahead, but do not pass the local train.

True BRT is not "cheap LRT" or "LRT Lite" [4]. Building a substantially grade-separated busway with well-designed stations can be very expensive, particularly within the congested central city. But with a robust and well-conceived service plan using several types of bus routes the resulting service can have some advantages over LRT with respect to easier introduction of line connections, branches, and express/local services if stops have four lanes (see Fig. 11). It is, however, doubtful that a BRT line can achieve on any given ROW width (two tracks/lanes, or four tracks/lanes) the capacity of a light rail line capable of coupling multiple cars into a single unit.

BRT Evaluation: Successes and Failures At this time (2011), the broad experiences of recent decades achieved by dozens of cities – and demonstrated by cities recognized as leaders in efficient transportation that contributes to their livability and sustainability – can be summarized in the following major points:

- Balanced intermodal transportation is greatly superior to transportation systems based on car dependency, meaning excessive restrictions on certain major modes such as transit, walking, or bicycling, or impracticalities on their use.
- Balanced transportation must incorporate and favor public transit systems which consist, particularly in medium and large cities, of different integrated modes, such as buses, BRT, trolleybuses, LRT, metro, and regional rail.
- Large cities, with more than one million people, usually have rail modes as their main carriers, but rail systems cannot achieve their full potential if they are not complemented by and integrated with buses.

There have always been promoters of individual modes claiming that they are superior to other modes. The strongest such pressures have been for private cars, and their political successes have created car-dependable cities that are inferior to intermodal cities with respect to quality of life, economic vitality, and sustainability. Single-mode promoters have also caused "waves" of discussions that the most efficient modes are paratransit, monorails, various automated guided systems (AGT), including the totally infeasible personal rapid transit (PRT, now reappearing under the name "Pod cars"). These extremist views that a single mode is the dominant or only solution for all cities have eventually been discredited. Intermodal transit systems utilizing the diverse family of transit modes, from historic streetcars to BRT and regional rail systems, are obviously the trend for the future.

To be fair, promoters of single modes have fostered some useful innovations. Paratransit has become more diversified since the 1970s. Some 2 dozen monorails have been built in various cities, and AGT systems are used in an increasing number of airports as well as for transit lines in some cities, particularly as downtown circulators.

It is unfortunate that BRT, which has brought very significant progress to many cities, is promoted by some organizations, government bodies, and individuals as the single mode superior to all other modes. This fringe of extremist BRT promoters is actually causing considerable harm by weakening the concept of intermodal transit and by actually strengthening the already dominant pro-automobile lobbies. Finally, these "BRT evangelists" harm the cause of BRT by promising that this mode can solve all transport problems, so that its problems or failures in different cities lead to questioning the value of the entire BRT concept.

Many elements of BRT were introduced during the 1970s and 1980s in several cities, although the term "BRT" had not yet been coined. São Paulo developed several high-density corridors with high-frequency service by buses and trolleybuses utilizing four-lane stations with overtaking of buses, platooning of buses

from different branches for increased capacity on the joint trunk, etc. Pittsburgh, Washington (Shirley Highway), and Los Angeles (El Monte) introduced busways, although more for commuter services than for regular transit. Ottawa built a network of busways and made more integration of their services with land use planning around their stations. (The limitation of this system has been that its busways lead into downtown streets, which represent a capacity bottleneck for the entire network.)

To clarify the strengths and limitations of the BRT mode, several leading BRT projects are evaluated here.

Curitiba: Following innovations in bus system design in various cities, Curitiba in Brazil built a network of BRT lines which is still considered the best planned one because it was designed as an integrated part of the city's land use plan. The BRT lines represent the spines of major corridors with high-density buildings throughout the city.

In addition to the planning aspects, Curitiba became the leader in designing high-level platforms and high-floor buses for level boarding/alighting through wide doors on articulated and double-articulated buses. Fare collection at the entrance to specially designed stations in the median of the busway was another element that increased line speed and capacity. Curitiba is considered as a leader in the development of the BRT concept.

Bogotá's TransMilenio BRT System: This BRT system has drawn great publicity and is called by some the "Gold Standard of BRT." It is therefore useful to examine its strengths and achievements, as well as its limitations and shortcomings.

The city of Bogotá, capital of Colombia, suffered from chronic congestion that was getting steadily worse with its growth of population and car ownership. It was served by remarkably primitive transit services consisting mostly of 8- and 10-m long private bus lines without any coordination, integration, or joint fares among hundreds of companies and individuals who owned and operated them. The city faced two problems: how to organize transit services into a coordinated system, and then how to build a network of high-capacity semi-rapid (mostly independent) or rapid (fully separated) transit lines.

Rail rapid transit was planned for a long time, but problems in coordinating, organizing, and financing the project stalled progress. Then, under the leadership of Mayor Enrique Penalosa, a BRT system was built for a major corridor, opening in December 2000. This was followed by other lines, which now represent a network of high-capacity lines.

The achievements of TransMilenio are quite remarkable. The system represents a huge leap forward over the chaotic, low-quality and low-capacity disintegrated bus lines. These small-bus services still carry the majority of trips in Bogotá and still represent a serious problem because of their poor service quality and inability to attract choice riders. The TransMilenio system has successfully attracted a substantial portion of trips and provided them with much faster and more reliable services. Now, finally, the city with a population of about seven million persons and growing has an increasing network of fast lines largely independent from street congestion, which also reduce the traffic loads and congestion on existing streets.

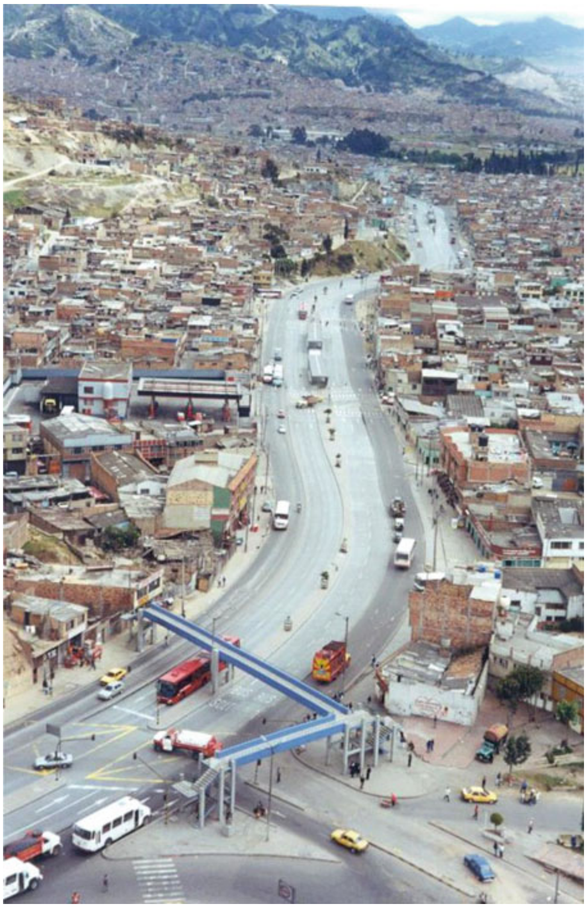
Along with these significant achievements, TransMilenio has several serious limitations, which should be carefully considered in further transit planning for the city. They are:

- The success in attracting very large passenger volumes is overwhelming the system. TransMilenio operates at and beyond its capacity for long periods of the day. That results in extremely low passenger comfort and lower service reliability than the system could provide with below-capacity passenger volumes.
- TransMilenio busways are located in the median of corridors with 8–12 traffic lanes that can be crossed by pedestrians only via long overpasses provided at distances of several hundred meters. This design provides only a single access to every bus station, so that walking distances from the closest buildings and streets to a bus station entrance amount in many cases to several hundred meters and involves crossing ramps and bridges unprotected from the weather. This design is very unattractive to users, reduces the competitiveness of transit services for car owners, and represents a major divide between streets and buildings on its opposite sides. This is the opposite impact on a city's livability from the impacts that LRT services have when they go through pedestrian zones.

- While electrically powered rail transits (LRT or metro) provide quiet vehicles without exhaust and long-term sustainability, buses with diesel or other internal combustion engines represent a much less attractive alternative. Thus, in the choice between BRT and LRT or metro, buses represent a major step backward with respect to a city's livability and sustainability (Figs. 13–16).

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 13
Back-up of buses at TransMilenio station reduces service reliability

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 14
Long overpasses are only access to many TransMilenio stations



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 15
TransMilenio corridor is a major barrier to pedestrians in Bogota

These limitations explain why there is so much interest in building a metro in Bogotá. Low- and medium-capacity BRT lines represent the optimal, most economic solution when matched with similar passenger demand. However, a BRT line operating beyond its capacity requires a major investment in a line that provides a higher quality of service, attracts more choice riders, and enhances the city's livability. Bogotá is a city with a steadily increasing population that brilliantly converted uncoordinated midi-bus services into a coordinated network of regular buses and BRT lines. It has used taken advantage of corridors that allowed the four-lane busway, but now must invest in rail transit to further improve its quality of transit service, economic vitality, and sustainability. The question is actually not whether Bogotá's higher-capacity transit system should be BRT or LRT/metro: the city obviously needs both, rail for its most heavily loaded lines, BRT serving a network of medium-capacity lines.

Mexico City's Insurgentes BRT: Similar to Bogotá, the Insurgentes corridor was served by uncoordinated minibuses with erratic, unreliable service. The first 20 km and 36 stations of the Insurgentes BRT facility opened in 2005; in 2008 an additional 9 km opened. As with the TransMilenio BRT system this line operates in the median of a major arterial road requiring passengers to access stops only through one entrance after long walks. Buses stop one at a time and cross many signalized intersections one at a time, so that the maximum capacity obtained using one articulated bus per signal cycle amounts to 5,000–6,000 persons/h.

The BRT line was so much better than the minibuses that the line attracted 280,000 persons/day, which exceeded its capacity and resulted in extreme, sometimes dangerous, overcrowding.

Also similar to TransMilenio, the Insurgentes line was built faster and at lower investment cost than an LRT line would have required. However, while its current operation can be deemed a success based on its daily ridership, its capacity limit was reached at the time the line opened. An upgrade to rail technology could allow double or triple the capacity still maintaining only one transit unit (train) per signal cycle through intersections. Only the street block length would limit the potential train length. Safety would also be increased with the decrease in the number of bus braking and accelerating cycles and with the added signal protection on any segment where train speed exceeds 70 km/h. LRT would have provided so much greater capacity, resulting in correspondingly greater riding comfort. Given the present ridership levels, one could argue that conversion to a metro line would even have merit.

The Bogotá and Mexico City examples show fairly typical decisions many cities face as they ponder how to improve their transit services. If there is an avenue in which ROW B can be obtained, BRT usually requires a lower investment and simpler/shorter implementation. However, LRT would provide a much higher

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 16
Exhaust pollution from TransMilenio operations

capacity, better riding comfort and passenger attraction over the long term. Moreover, with respect to the city's livability and sustainability LRT is clearly superior to diesel (or even CNG) buses, particularly in sensitive inner city areas.

Istanbul Freeway Median BRT: Istanbul is by any definition a megacity spanning a very large region. Due to the long travel distances and extremely heavy congestion, the traveling public wastes much time. Even the limited access highways can be chaotic with thousands of buses stopping along the roadside, thus resembling ROW C much more than ROW A in character. In 2007, the first 18 km and 14 stations within one such freeway opened as a BRT system (Phase I). Typically, its stops and dedicated lanes were located in the middle of the limited access highway. In 2008, an additional 29 km and 25 stations were added (Phase II). At that time it was projected that an additional 11 km would be built for a total of 50 km at a relatively modest total cost of $125 M (Fig. 17).

Phases I and II already carry 858,000 passengers per day, and many passengers are saving over 1 h per day in commuting times. Thus, it would seem to be a major success. However, this very success indicates that the conditions are strong for an upgrade to rail technology. There are close to 2,500 bus trips made per day on this busway with headways often down to 20 or 30 s of separation. Consequently, there is a significant amount of air pollution and fuel consumption from the enormous volume of buses. Furthermore, bus speeds and passenger comfort are limited and safety is compromised due to hundreds of thousands of accelerating and braking cycles per day at highway speeds.

The ready availability of the right-of-way and the long station spacings due to their location at overpasses would allow for the running of large high-capacity trains that accelerate faster and obtain higher speeds than do buses. The high demand and ROW A clearly justifies rapid transit technology, not LRT technology. Headways would still be short while time savings and passenger comfort would be greatly increased. Safety would be enhanced by automatic train protection. Total energy consumption and both air and noise pollution would be reduced. Operating cost savings would be substantial and could be used to bolster other parts of Istanbul's network including more feeder services.

It is true that far fewer bus drivers would be needed, but this decrease in employment would be far offset by the increase in economic vitality and job opportunities opened with the corridor's faster travel times. (There would also be some offsetting employment created to maintain and repair the guideway and vehicles.)

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 17
BRT with ROW category A in Istanbul, Turkey

Comparison of LRT and BRT Modes

Light rail transit and bus rapid transit (but not Bus Transit Systems) are functionally similar modes. As semi-rapid transit (mostly independent of street traffic), both provide much higher service performance and have more positive impacts than the basic street transit mode – regular (conventional) buses (RB). Both require investments that are significantly higher than those for RB, but much lower than for metro systems. However, LRT and BRT are drastically different in their technology, operations, quality of service, and their short- and long-term impacts on the city. In most cases, they typically provide different "investment cost/performance packages" so that their comparison is very complex.

Applications of the two modes vary between two extremes. In medium-sized cities or corridors BRT can fully meet the capacity and performance needs at lower cost than LRT. At the other extreme, in many medium- or large-size cities LRT offers far superior performance, operates efficiently in pedestrian-oriented areas or in short tunnels under city centers, and has many more positive impacts for a city's livability than does BRT. Between these two poles, where BRT and LRT are, respectively, obviously the superior choices, are many applications with different trade-offs so that either one of the two systems may be the preferred mode.

Review of Modal Characteristics

Table 1 presents a comparison of the basic characteristics of RB, as the most widely used street transit mode, BRT and LRT. The characteristics are grouped in three categories: system components, lines and operational components, and system characteristics.

As Table 1 shows, the elements in which BRT differs from RB are ROW category, larger vehicle capacity if double-articulated buses are used, different line designs and stop spacings, higher investment costs, and its greater passenger attraction.

Focusing on the BRT and LRT modes, their comparison can be summarized in a number of characteristics, as presented in the following box [5].

Some of these comparisons are factual and obvious, proven in real-world situations. Several of the major differences will be discussed here.

Advantages (+) and Disadvantages (−) of LRT over BRT

+ Separate ROW (B or A) for LRT is easier to achieve because LRT uses rail tracks instead of roadway lanes, and due to its different technology requires no physical protection and police enforcement, as do busways (Fig. 18).

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 1 Comparison of regular bus, bus rapid transit, and light rail transit characteristics

Mode ▶ / Characteristic ▼	Regular bus(RB)	Bus rapid transit (BRT)	Light rail transit (LRT)
System components:			
ROW	C	B (C, A)	B, (A, C)
Support	Road	Road	Rail
Guidance	Steered	Steered	Guided
Propulsion	ICE	ICE	Electric
TU control	Driver/visual	Driver/visual	Driver/signal
Vehicle capacity (spaces)	80–120	80–180	100–250
Max TU size	Single vehicle	Single vehicle	1–4 car trains
Max TU capacity	120	180	$4 \times 180 = 720$
Lines/operational elements:			
Lines	Many	Few	Few
Headways	Long/medium/short	Long/medium/short	Medium/short
Stop spacings (meters)	80–250	200–400	250–600
Transfers	Few	Some/many	Many
System characteristics:			
Investment cost/km	Low	High	Very high
Operating cost/sp	Medium	Medium	Low
System image	Variable	Good	Excellent
Pass. attraction	Limited	Good	Strong
Impacts on land use and city livability	Least	Moderate	Strongest

+ LRT has better vehicle performance than BRT because of its electric traction.
+ LRT produces no exhaust along the line and much lower noise than BRT (except that in a few cities, trains are required to use horns at grade crossings).
+ LRT is often designed to serve as the central element for access and image of pedestrian areas in central cities; a busway with high-frequency bus services is much less compatible with "pedestrianized" areas.
+ LRT can use tunnels, BRT cannot.
+ LRT vehicles are more spacious and comfortable and have better riding quality than buses.
+ LRT has a stronger image; it is more popular and attracts more riders.
+ LRT has a stronger positive impact on urban development than BRT.
– Investment costs for LRT are higher than those for BRT.
– For the first LRT line in a city, introduction of a new technology requires more extensive construction of infrastructure as well as new equipment, and it involves longer implementation.

Diesel Bus Technology Versus Electric Rail Technology

The basic benefits and drawbacks of diesel and electric traction, and rubber-tired and rail technology are

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 18
Recently opened LRT line in Dublin, Ireland on a ROW category A section

inherent in the BRT and LRT modes. All BRT systems use the internal combustion engine for propulsion. In the past the fuel was diesel. Recently, new BRT systems in the industrialized world use less polluting liquid natural gas (LNG) or compressed gas (CNG) as fuel sources, but engine performance does not fundamentally change.

More detailed analysis of BRT and LRT characteristics caused by their different types of traction and road/rail technology are given in the following two boxes, respectively [6].

Several relevant points from the above comparisons deserve some discussion here.

- LRT in most cases costs more to construct initially. Although rail equipment and facilities last longer, the required higher initial investment is often a major problem. An exception to LRT costing more than BRT might be where ridership demand requires a category A BRT to avoid at-grade crossings, but LRT can provide that capacity with a less expensive category B design.
- LRT has much more capacity because rail technology allows the coupling of railcars into trains; coupling cannot be done with buses. This is particularly important for transit projects using category B rights-of-way. Traffic engineers limit the amount of green time given to transit. If the expected ridership demand on the line is high, the transit unit used must carry the most passengers. In this regard, LRT has the added advantage of requiring crossing gates for safety.
- BRT has the potential to offer more service options, not just the end-to-end operation typical for LRT. A BRT line can offer end-to-end service, but can supplement it with express bus services or multiple route-to-trunk line services typical of freeway bus operations.
- If capacity and service quality require that ROW A is used, that is usually more complicated for buses than rail vehicles and results in bus services which are much inferior to rail. The best example is the Silverline BRT in Boston, where a 1-mile long tunnel required an investment cost of about $500 million, and buses now operate in it at speeds limited to 10–25 km/h. Capacity of buses operating in single-lane tunnels is only a fraction of the capacity LRT would provide.
- Road and rail technologies also have a direct impact on operations of their rights-of-way. Separation of ROW for LRT needs no enforcement because in most designs road vehicles cannot use tracks

because they are not paved. BRT's advantage, that it uses the same road surface as other street lanes, is actually a serious disadvantage with respect to control of their use. Many bus lanes and busways have been first downgraded by allowing other vehicles to share them (first taxis and vehicles making turns at intersections, then HOVs, any cars who pay tolls in such lanes, and then even hybrid private cars). In many cases these steps led to eventual losing of ROW B for buses and discontinuation of the BRT system (see Fig. 3).

Electric Rail Traction Compared with the Internal Combustion Engines of Buses

+ Produces higher, smoother acceleration (limited by passenger comfort)
+ Produces far less noise and vibration
+ Produces no local air pollution
+ Can easily use tunnels due to absence of pollution and good dynamic performance
+ Allows for regenerative braking, thus reducing energy consumption
+ Is much cleaner to operate and maintain
– Requires additional investment for electrification of lines and construction of substations
– Overhead power lines are sometimes criticized for aesthetic reasons, although many passengers like the distinct identity the catenary gives the line
– Is susceptible to power failure that stops all vehicles on a section of line

Rail Technology Compared with Rubber-Tired Buses

+ Makes coupling of cars into trains possible, drastically increasing line capacity
+ Rail guidance allows use of wider and longer cars and requires narrower free profile
+ Has much higher safety because of automatic signal control, although at additional investment and maintenance costs
+ Provides a far more stable, smoother ride quality
+ Is far more energy-efficient due to steel wheels on steel rails
+ Can better cope with adverse rain, ice, and snow conditions
– Requires substantially higher investment, although the vehicles and guideways are more durable and require lower ongoing maintenance
– Cannot negotiate as steep a gradient, nor as sharp curves as buses
– Requires a higher degree of safety because of longer stopping distances
– Can be much louder when going through sharp curves
– Is normally slower around any given radius of curvature and may therefore have a slower travel time between stations than bus technology

Line Capacities

An extensive debate has been going on with respect to the line capacity of different transit modes. To check the validity of various claims of modal capacities, two values will be quoted for each mode: the first, for the bus mode, assumes regular buses with 90-space capacity (6 persons/m^2) and with single stops with fast boarding/alighting, allowing average headways as short as 1 min. Such a system provides a line capacity of 5,400 spaces/h.

The second value for bus line capacity assumes that each stop has four lanes, allowing overtaking and "leap-frogging" of buses. In this way, capacity can be increased significantly. This is seldom possible in urban areas, but some examples exist. Portland, Oregon, organized a pair of bus streets with two lanes for buses and overtaking of buses in stop areas, which achieved capacity of 180 buses/h or average headways of only 20 s. With an average capacity between regular and articulated buses of 110 spaces, this results in a line capacity of 19,800 spaces/h.

The Comonor project, a high-capacity bus corridor in São Paulo, Brazil, claimed to have achieved capacity of 24,000 spaces/h by operating buses in platoons overtaking each other at stops along the line. However, that description turned out to be theoretical, and actual

capacity provided on São Paulo streets was considerably lower.

New claims of much higher capacities for new BRT systems came particularly with the opening of the TransMilenio system in Bogotá, Colombia. That system was systematically designed for high capacity: most buses are articulated and double-articulated, all fares are collected at station entrances, and the system has two lanes on some sections, but four lanes in station areas allowing bypassing and overtaking of buses. This is particularly the case on the main line built in a wide median of a very wide freeway right-of-way. However, the line has a number of signal-controlled intersections, which limit the green time for the BRT line.

Even if it is assumed that all buses are double-articulated and occupied with an extremely high average density of 6 persons/m^2, and that it is possible to have an average headway of buses crossing signalized intersections of 20 s, such an operation would amount to about 28,000 spaces/h. Although these assumptions are higher than in real world (for one, not all buses are double-articulated), advocates of BRT systems have claimed capacities exceeding 30,000, later 35,000 and even as high as 53,000 persons/h. The latest revisions to a couple of prominent BRT design manuals written for applications to developing countries appear to be correcting these overblown numbers downward, toward lower, although still unrealistic values of over 30,000 persons/h.

For comparison, the capacity of LRT lines operated with trains consisting of two articulated cars (such as in Manila) with realistically achievable 2-min headways is about 15,000 spaces/h. With more optimistic assumptions, corresponding to those used by BRT promoters, LRT lines using four-articulated car trains as operated in several cities and 1.5 min headways would achieve an offered capacity of 32,000 spaces/h. With four tracks for bypassing in stations, this capacity could be increased further, but the critical locations would be at intersections. As the measurements of actual operations of the Orange Line BRT (Los Angeles) show, LRT can provide substantially higher capacity at street crossings than buses because of the higher capacity of LRT trains compared to individual buses, even double-articulated ones.

Under similar assumptions, ten-car trains of a metro system operating at 1.5-min headways would provide a capacity in the order of 60,000 spaces/h, while the four-track metro line in New York carried 89,000 persons/h in the 1940s (presently, passenger numbers are smaller, because trains in most of the industrialized countries are operated with higher comfort levels which result in 4–5 persons/m^2).

Another deceptive feature of these claims of BRT capacities is that they represent the obsolete, simplistic measure of line capacity as a single number, without regard to service quality and level of service. With respect to highway capacity, it was already in 1950 realized that capacity in terms of vehicles per hour should be related to the level of service (LOS), which was defined as LOS A through F. Capacity of transit lines is now also related to performance and LOS. For example, if one transit line carries 14,000 persons/h with an operating speed of 16 km/h and another line carries 14,000 with a speed of 24 km/h, their performance is by no means the same. Lehner [7] introduced the concept of productive capacity – product of transporting capacity and speed – to include this characteristic. It can be insightful to plot the productive capacity against investment cost. Vuchic [8] specified that evaluation of transit capacity should include the following five factors:

- Offered line capacity in spaces/h
- Operating speed in km/h
- Load factor or capacity in persons/space, where spaces include both seated and standing spaces assuming a certain degree of crowding
- Comfort standard in square meters/person (or degree of crowding in persons/m^2)
- Reliability of service in percent of departures on time

Consequently, capacity of transit modes cannot be evaluated only by hourly throughput of persons; it must include level of service.

Comparisons of capacities of different modes must also be made for comparable conditions and assumptions. For example, comparing capacities of BRT and LRT must assume that both modes have either two lanes/tracks, or four lanes/tracks in stations. Thus, the Insurgentes BRT line in Mexico City should be compared with a two-track LRT line, such as in Cologne or Manila. The TransMilenio BRT line in Bogotá should be compared with a four-track LRT line, which would have capacity well over 40,000 spaces/h.

Compared modes must also have the same load factors and comfort standards. Reliability and operating speed would then have to be measured or predicted on the basis of characteristics of each mode.

Recent Studies Comparing Different Modes of Real-World Transit Systems

Studies comparing transit modes generally fall into two categories. The first compares modes that are being planned or hypothesized, that is, not in operation. These types of studies are needed, of course, when doing major planning work, but they must use projections of ridership and costs rather than actual ridership and costs. The alignments and operational assumptions made for each alternative should be as similar as the characteristics of different modes allow.

The second category of studies compares modes operating in one or more cities. A major problem with these types of studies is that each system operates in a different cultural, economic, and operational context, but their great advantage is that their features and numerical values are realistic, not hypothetical and subjective.

One recent study that looked at one city with several bus and rail modes operated by a single agency is described below.

Case Study: Comparison of Transit Modes in Los Angeles Over the past 25 years Los Angeles' metro transit network has evolved from an all-bus system to a network of many transit services and modes. As of spring 2008, this network included a rapid transit line, three light rail lines, three busways, 19 enhanced bus transit routes, and 95 local bus routes. For the first time the opportunity exists to compare a variety of transit modes all operated by the same agency within the same urbanized area eliminating differences in labor costs between urban areas, in operating and management practices, in efficiencies of scale, and in time and methods of data collection [9].

Various performance and cost measures were calculated for each mode operated by the Los Angeles metro. The results of this analysis are shown in Table 2 for performance measures, in Table 3 for cost measures.

The Orange (BRT) Line is much slower than the average of the LRT lines. This is because it does not

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 2 Performance measures of Los Angeles metro transit modes (2008)

Performance measure	Local bus	Rapid bus	Orange Line BRT	Light rail	Rapid transit
Ave. peak hour speed (km/h)	20.6	24.0	29.3	41.4	51.8
Ave. trip length (km)	5.7	7.3	9.4	11.3	8.0
Daily riders: (experienced) (possible max)	30,000 30,000	30,000 30,000	25,000 35,000	84,000 100,000	140,000 300,000

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 3 Cost measures of Los Angeles metro transit modes (2008$ unless noted)

Cost measures	Local bus	Rapid bus	Orange Line	Light rail	Rapid transit
Capital cost ($M/km)	N/A	$ 0.15 (2000)	$17.3 (2005)	$ 38.9 (2003)	$130 (2000)
Operating cost per pass-km	$0.60	$0.39	$0.30	$0.31	$0.27
Operating subsidy per pass-km	$0.47	$0.29	$0.22	$0.25	$0.20

have full signal priority and catches red lights at a third of its intersections. Its buses must also slow below 32 km/h (20 mph) at all crossings. It also has nowhere near the carrying capacity of the light rail lines and is nearing capacity with about 25,000 daily riders. One LRT Line (Blue) has had a weekday ridership above 80,000 for a number of years.

On the other hand, the Orange Line was built for less than half of the capital cost per kilometer of the Gold (LRT) Line during the same period. Time will tell whether that investment was prudent given the much slower speed and the looming capacity limit of the busway. The Orange Line may be an example of a BRT line that should have been built fully grade-separated for higher speed and capacity, but if it had been, its cost might have exceeded the cost of an equivalent light rail line operating on the existing ROW B.

Summary Comparison of BRT and LRT Modes

Table 4 gives a summary comparison between the BTS, BRT, and LRT modes. Overall, the two bus modes have advantages with respect to investment cost, construction time, and the complexity of system implementation. However, LRT demonstrates superiority in most measures of service efficiency and level of service: speed, comfort, image, and passenger attraction. Even more important may be that LRT is superior in its positive impacts on land use planning, urban form, livability, and sustainability. Focusing on the BRT-LRT comparison, BRT tends to be a faster and usually (but not always) lower investment solution, but LRT provides higher service quality, stronger passenger attraction, and a more powerful step in increasing the city's quality of life and sustainability.

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 4
Summary comparisons of the BTS, BRT, and LRT modes

Mode characteristic	Bus transit system BTS	Bus rapid transit BRT	Light rail transit LRT	Superior mode
Investment cost	Medium	High	Very high	BTS
Implementation Complexity and time	Short	Medium	Long	BTS
Operating cost	Lower for low passenger volumes	Lower for low passenger volumes	Lower for high passenger volumes	Depends
Operating speed	Medium	High	High	Depends
Ability to accommodate service options	Low	Some with four-lane stops	Low except with four-track stops	BRT
Capacity	Low	Medium	High	LRT
Type of energy and traction	Internal comb. engine	Internal comb. engine	Electric	LRT
Vehicle performance	Good	Good	Excellent	LRT
Air pollution and noise	Poor	Poor	No local pollution, low noise	LRT
System image and passenger attraction	Fair	Good	Excellent	LRT
Potential to influence land development	Limited	Fair	Very good	LRT
Contribution to livable urban environment	Some	Limited	Excellent	LRT

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 19
Five-section low-floor LRT vehicle provides high capacity and can make sharp turns on ROW category B in urban streets in Helsinki, Finland

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 20
Buses and light rail trains share ROW category B in Helsinki

Trends and Expected Future Directions

City populations in many developing countries are growing rapidly. Those countries that also have growing economies and rising income levels are seeing ominous growth in auto ownership. One defense against the inevitable, debilitating congestion that these new cars bring is to invest in attractive urban transit systems capable of meeting future demands.

For large cities with many million inhabitants, high population densities, and heavily traveled corridors,

rail rapid transit (metro) is clearly the most efficient transit mode for the basic network. Megacities like Tokyo, Beijing, and São Paulo will have to extend their metros as the population continues to grow.

The trend of developing medium-capacity modes, which started with the growth of LRT and later BRT, will continue. These modes are being introduced to supplement metros in suburban areas and as transitional solutions when metros cannot be built fast enough for financial or physical reasons.

The two modes most capable of meeting the need in many cities in developing countries are LRT and true BRT. Both, however, are costly investments. One future direction is therefore to convey to transit policymakers that the investment decision they face is between these two modes, not the false promise of inexpensive, inadequate lower-cost bus modes.

In developed countries, a future direction for study is to appraise honestly the cost and performance of true BRT systems and their more comprehensive service options. In some applications the LRT model of a high-capacity rail line fed through transfers from connecting bus routes may not provide the most attractive, convenient service. In other cases, if a BRT would be loaded to capacity as soon as it is opened (which is the case with some lines in Bogotá and Insurgentes in Mexico), a rail system – LRT or metro – would obviously be a more efficient and permanent solution. Understanding where each of these options works best will be quite useful.

Finally, the damaging argument within the transit community between BRT and LRT must subside if transit is to compete most aggressively with the private car. In a world that needs to have far fewer private cars depleting our oil reserves, strangling our cities, and fouling our air, the focus must be to provide the most attractive, cost-effective transit, bus, or rail for a given circumstance. It should not be to have one mode to the exclusion of another. A good example for this is Bogotá, where the debate should not be BRT versus LRT, but BRT *and* a rail system (LRT or metro). This is particularly the case with lines where volumes are very high and environmental aspects are very important. In such cases the transit system must enhance the livability of the city, minimize its air and noise pollution, and join rather than divide its neighborhoods (Figs. 19 and 20).

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Bus Versus Rail Implications for Transit-Oriented Development

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Article Outline

Glossary

BRT Bus rapid transit (BRT) refers to a variety of mass transit systems that utilize buses to provide faster, more efficient services than a conventional bus line. BRT runs on existing roadways or dedicated rights-of-way and offers such operational features as high-capacity, low-floor bus vehicles, traffic signal prioritization, and real-time information services.

LRT Light rail transit (LRT) refers to electrically propelled rail vehicles operating singly or in trains. It obtains power from overhead cables and runs on reserved but not necessarily grade-separated rights-of-way. LRT provides service capacities and speeds typically lower than metro rail.

Metro rail Metro rail typically consists of steel-wheeled, electric-powered vehicles operating in trains of two or more cars on a fully grade-separated right-of-way. Alternative names for metro rail include subway and heavy rail. It offers higher capacities and speeds than light rail.

New urbanism New urbanism refers to an urban design movement led by a group of architects and urban planners in the USA since the early 1980s. New urbanism promotes walkable neighborhoods and attacks suburban sprawl through nonconventional physical planning and design approaches. Traditional neighborhood design (TND) and transit-oriented development (TOD) are two examples of new urbanist practice.

TOD Transit-oriented development (TOD) refers to mixed-use, medium- to high-density development around the transit station with pedestrian- and cyclist-friendly environmental design. The term was coined by Architect Peter Calthrope while other terms, for example, Transit-Focused Design and Transit Villages, have also been used to describe similar development concepts.

Transit ridership The quantity of passengers riding on the transit over a given period of time, for instance, a day or a year.

Transit value capture Transit value capture refers to the process by which all or a portion of increments in land value attributed to public transit investments are recaptured by the public sector. The idea can be traced back to the thinking of Henry George and his followers. The rationale states that transportation projects improve accessibility to the adjacent land. This improved accessibility is capitalized in property values, generating a windfall for private landowners. Public agencies can capture a portion of that windfall by utilizing a variety of methods. The captured value can then be used to finance transportation or other public infrastructure.

VMT Vehicle miles traveled (VMT) measures the distance in miles that vehicles are driven over a given period of time, for instance, a day or a year.

Definition and Importance

Transit-oriented development (TOD) refers to mixed-use, medium- to high-density development around the transit station with pedestrian- and cyclist-friendly environmental design oriented to transit services. Integrating transit with land use has been a common

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practice in most European, Asian, and Latin American cities. It is not a brand-new idea in the USA either. In the streetcar era, for example, developments largely concentrated along transit corridors in Boston, Chicago, San Francisco, and many other streetcar communities. TOD began to regain popularity in the early 1990s when the US Architect Peter Calthorpe coined the term in his book *The Next American Metropolis: Ecology, Community, and the American Dream* [1]. Other terms have been used by transportation professionals, urban planners, and the real estate industry to express similar development concepts, for example, "transit-sensitive land use" [2], "transit-oriented design" [3], "transit-focused development" [4], and "transit villages" [5]. TOD represents these multi-professional interests in developing around transit. Amid a worldwide trend of rising motorization and growing vehicle miles traveled (VMT), TOD is being widely promoted as a strategy to achieve sustainable transportation. Currently, there are over 4,000 transit sites in the USA offering significant potential to practice TOD [6].

At the center of TOD is transit. There are a variety of transit technologies; broadly they can be grouped as bus-based or rail-based. Bus- versus rail-based transit presents distinctive operational and service characteristics and involves quite different levels of public investments. Accordingly, bus-TOD versus rail-TOD entails different planning and design considerations. Whether to develop bus- or rail-based mass transit has long been a topic of policy debate. Recent developments in bus rapid transit (BRT) and light rail transit (LRT) throughout the world add to existing heated discussions on the advantages of bus- versus rail-based transit systems. This entry describes the comparative characteristics of bus- versus rail-based transit and discusses their implications for TOD.

Introduction

Transit-oriented development (TOD) is a strategy to integrate transportation with land use by focusing development on transit. A number of factors have motivated many communities in the USA to pursue TOD. Fighting sprawl and sprawl-induced problems is among the top. Community development in the USA after World War II can be largely characterized as low-density, strictly separated land uses, and car-oriented design. In a sprawling built environment, transit becomes operationally unviable and driving becomes a necessity. The consequences are ever-growing vehicle miles of travel (VMT) and increasing roadway congestion, energy consumption, and vehicle emissions. TOD offers potentials to curb sprawl and to help reduce the driving-related problems. Many state and local governments are encouraged to implement TOD by the recent steady increase in federal funding for transit. For example, the three transportation bills in the less than 20 years, namely, ISTEA to TEA21 to SAFETEA-LU, authorized increase in transit funding from $25 to $36 to $52.6 billions, respectively.

TOD is being widely advocated in Europe, Asia, and Latin America as well although their cities have traditionally developed in relatively high densities and rich mixed uses. The TOD interest grows out of the concern that new developments in many of these cities tend to depart from the traditional urban form. Amid rising income and associated growth in private motorization, neighborhoods and workplaces are becoming increasingly car oriented and pedestrian/cyclist hostile. Densities in these cities are high relative to the North American cities; yet the high density may not function well if it is not fully integrated with the transit. Dysfunctional density likely leads to what the New Urbanist Andres Duany called "high-density sprawl" [7]. Careful TOD planning, design, and implementation are essential for transit and its surrounding built environment in order to benefit from density.

A TOD typically has five attributes: transit access, a district of walking distance from the transit, mixture of different compatible urban functions, medium to high development density, and pedestrian- and cyclist-friendly environmental design in the TOD district. These attributes are interrelated and their composition for a specific TOD will vary by the spatial, socioeconomic, and technological context in which the TOD is proposed. TOD planners have created TOD typologies, specifying variations in design attributes for TODs in different spatial context, for instance, downtowns, urban neighborhoods, employment centers, and other regional locations [8]. As transit is at the center of TOD, TOD attributes will also vary by transit technologies.

Transit Technologies

Transit technologies evolve along with advances in vehicle technologies, information and communications technologies, as well as power and energy technologies. Table 1 shows the most commonly seen urban transit modes grouped into two categories: bus-based and rail-based. A comprehensive list and characterization of urban transit can be found in Vuchic [9].

TOD attributes and the ways in which these attributes interact will differ depending on the specific transit that the TOD is proposed for.

- A particular type of transit technology is associated with certain levels of cost. In general, the cost consists of two parts: capital and operation. Capital costs include vehicle cost and infrastructure cost (land acquisition and clearance and system complexity). Operating cost includes labor, insurance, fuel, administration, and others.
- Different transit technologies and operating plans deliver various levels of service capacities. Main factors affecting service capacities include vehicle size, service frequency, and road conditions.
- Carrying capacity, along with other operational and contextual factors, determines the level of services (LOS). Existing empirical studies have shown that the extent of land-use impacts of transit development is positively associated with LOS. In other words, higher capacity systems such as metro likely have stronger positive impacts on the value of land near the station.
- More expensive land leads to higher development intensity, which will result in higher population or employment density.
- Higher population and job density provides a larger pool of transit ridership. If there are more people riding on the transit, farebox revenue will increase. Higher density also provides a larger basis for economic activities and a larger tax base for the local community. The farebox and tax income help reduce cost burden of building and operating transit systems. Ridership increases, however, may trigger a greater need for expanded services, which can lead to increases in operating and potentially capital costs.

Cost Characteristics of Bus Versus Rail Mass Transit

The main topic of debate on bus versus rail transit development is cost. Recent discussions largely focus on cost comparisons between BRT and LRT due to a number of performance similarities between them. On a per user basis, rail transit systems generally cost more to build than bus transit but less to operate owing to relatively higher capacities associated with rail. Still, within each type of transit, there are large variations in technical specifics and operational characteristics.

Capital Cost Comparison Between Bus and Rail Transit

Table 2 shows the average capital cost per route mile for BRT, LRT, and MRT based on selected systems reviewed by USDOT [10], GAO [11], and BAH [12]. On average, BRT costs $10.24 millions (in 1990 dollars) per mile to build, less than half of LRT ($26.4 million) and less than one-tenth of MRT ($128.2 million). Nevertheless, average cost–based comparisons between bus and rail will likely generate controversies [13]. Table 2 also shows the ranges of capital costs of the transit systems studied. Notably, within same type of transit technology, capital costs vary considerably. For instance, the BRT in Miami, FL costs $5.6 million per mile to build, whereas the West Busway BRT in Pittsburgh, PA costs $41.7 per mile, higher than the average capital cost of LRT. The most expensive LRT among the 21 projects reviewed by USDOT [2] is in Buffalo, NY, which costs $90.19 per mile, over 40% higher than the per-mile capital cost of the metro in Miami.

Many factors contribute to the large variations in the capital costs of transit systems. Costs of BRT projects, for example, include vehicles (regular or articulated), the roadway cost (busways or bus lanes), station structures, park-and-ride facilities, communications, and traffic signal systems. For rail transit systems, guideway elements may take a large share of capital costs, depending on types of structure (e.g., tunnel or elevated). Different ways of accounting the costs by including (or excluding) various capital cost elements will change the average cost figures quite significantly. Hence, when comparing different types of transit systems with respect to capital costs, it is

Bus Versus Rail Implications for Transit-Oriented Development. Table 1 Transit technologies and descriptions

System technology and description	Example systems	Service geography	Average speed	Station spacing	Typical headway	Guideway	Typical power source
Bus-based							
Regular bus: A road vehicle designed to carry multiple passengers. Buses vary in capacity from a dozen to several hundred passengers.	Cities with transit services	Urban	15–30 km/h	0.2–1.0 km	8–20	On street	Gasoline
Trolley bus A passenger *bus* operating on tires and having an electric motor that draws power from overhead wires.	New Orleans	Urban	15–30 km/h	0.2–1.0 km	8–15	On street	Electric
Bus rapid transit BRT is a relatively new umbrella term for urban mass transportation services utilizing buses to perform premium services on existing roadways or dedicated rights-of-way.	Pittsburg, Curitiba, Bogota, Beijing	Urban, Regional	25–50	0.4–1.5	10–20	Shared or exclusive ROW	Gasoline
Rail-based							
Streetcar Bus on rails typically operating on city streets	Portland	Urban	15–25	0.4	8–15	On street	Electric
Light rail With an overhead power supply and LRT utilizes predominantly reserved but not necessarily grade-separated rights-of-way. Electrically propelled rail vehicles operate singly or in trains. LRT provides a wide range of passenger capabilities and performance characteristics at moderate costs.	Dallas: DART; Denver:	Urban, Regional	30–60	1–1.5	5–30	Exclusive or shared ROW	Electric
Heavy rail	Washington, D.C. Metro; San Francisco: BART; New York City: MTA Boston: MBTA Chicago: CTA	Urban, Regional	80–130 km/h	1–3	3–10	Grade-separated, Exclusive ROW	Electric

Bus Versus Rail Implications for Transit-Oriented Development. Table 1 (Continued)

System technology and description	Example systems	Service geography	Average speed	Station spacing	Typical headway	Guideway	Typical power source
Commuter rail	Boston Purple Lines: MBTA; New York Long Island Railroad San Jose: CalTrain	Regional	50–120 km/h	3–10 km	15–30 min.	Exclusive ROW	Diesel or hybrid

Bus Versus Rail Implications for Transit-Oriented Development. Table 2 Capital cost comparisons of bus versus rail (in 1990 US$)

	BRT	LRT	MRT
Average cost per route mile (millions)	$10.2	$26.4	$128.2
Cost range (millions)	$5.6 ~ $41.7	$9.4 ~ $90.2	$63.9 ~ $169.6
Number of projects reviewed	9	21	4

Sources: Calculated from [10–12]

important to maintain consistency in cost reporting and to examine/compare specific cost elements whenever data is available. Such itemized comparisons allow clear identification of specific factors driving up the system development cost.

Table 3 shows the breakdown of capital cost by subsystems for the three types of rapid transit technologies. Data for LRT and MRT come from a USDOT study of nine completed projects [2], whereas cost data for BRT are for two proposed systems in Atlanta, GA and Abuquerque, NM. Note that, although BRT costs less on average than LRT ($16.6 and $19.5 million per mile, respectively), for several items BRT costs exceed those of LRT. For instance, the average land acquisition cost (right-of-way) for the BRT projects ($3.018 million per mile) is almost twice as much as that of LRT project ($1.52 million per mile). This is partly because BRT requires a wider right-of-way than LRT. BRT guideway cost ($6.495 million per mile) is much higher than that of LRT ($4.289 million per mile) due to construction of dedicated busways. Station cost for BRT is also slightly higher than that of LRT. In most cases, a BRT station is located in highway median areas and requires elevated structure for passengers to access the station from both sides of the road. Capital cost for conventional bus is not reported here because it runs mostly on existing roadways free-of-charge and does not require guideways.

Operating Cost Comparison Between Bus and Rail Transit

Table 4 below compares operating costs between the bus and the rail transit modes. Cost per vehicle revenue mile measures the average cost of operating individual vehicles. It is the annual cost of operating a vehicle divided by the total annual number of miles traveled while the vehicle is in revenue service (e.g., excluding the miles traveled to/from the maintenance yard). Among the four transit modes listed in the table, LRT exhibits the highest cost at $9.3 per vehicle revenue mile. MRT has a relatively lower cost than LRT mainly because it can operate with as long as ten or more cars per train. Standard bus and BRT have the lowest vehicle-mile costs. Operating cost per vehicle hour is another way of measuring the cost of transit operation regardless of the number of passengers carried. MRT, which typically operates at a higher speed than other transit modes, displays the highest vehicle-hour

Bus Versus Rail Implications for Transit-Oriented Development. Table 3 Per mile capital cost breakdown of bus versus rail (in 1990 US$1,000s)

	BRT		LRT		MRT	
	$	%	$	%	$	%
Land (right-of-way)	3,018	15.0	1,520	7.8	7,436	5.8
Guideway	6,495	33.5	4,289	22.0	33,333	26.0
Trackwork or special conditions	983	8.5	1,686	8.7	5,385	4.2
Stations	1,387	9.1	1,094	5.6	33,333	26.0
Power and control	113	2.7	2,047	10.5	10,513	8.2
Facilities (yards and shops)	192	1.9	974	5.0	2,820	2.2
Eng./Mgt./Test (soft costs)	2,948	20.3	5,581	28.6	19,230	15.0
Vehicles	1,483	9.0	2,295	11.8	16,154	12.6
Total	16,620	100	19,486	100	128,203	100

Sources: Calculated from [10–12]

Bus Versus Rail Implications for Transit-Oriented Development. Table 4 Operating costs (1990$)

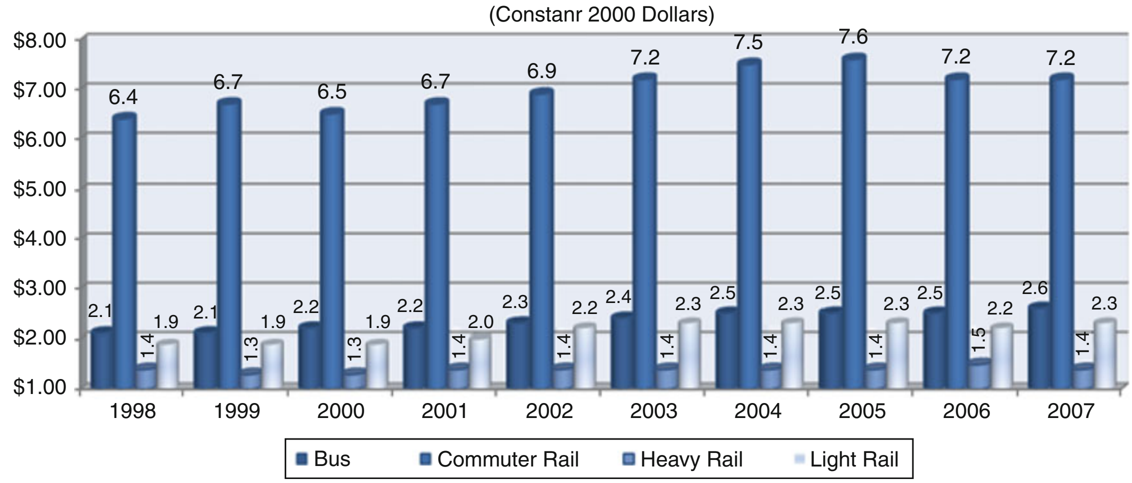
	BUS	BRT	LRT	MRT
$ per vehicle revenue mile	3.1	3.6	9.3	6.5
$ per vehicle revenue hour	45.0	78.8	125.0	152.0
$ per 1,000 place mile	60.0	72.3	96.0	49.2
$ per 1,000 passenger mile	616.4	496.9	578.0	282.0

Sources: Calculated from [10, 11]

cost. BUS and BRT once again rank the lowest in operating cost measured on the per vehicle revenue hour basis.

The other two measures of operating costs – cost per thousand place mile (where places account for total number of seats and permitted standings) and cost per thousand passenger mile – take into consideration the differences in vehicle capacity and system usage among the transit modes. Notably, MRT has the lowest cost at $49.2 per thousand place mile, whereas LRT's place-mile cost is the highest at $96. If usage is considered, BUS has the highest cost at $616.4 per thousand passenger mile. Again, MRT is the least expensive at $282 per thousand passenger mile. It should be noted that figures for BRT in the table above are derived from data in the GAO study [3]. The study does not report cost per passenger mile. The figure of BRT's $496.9 per thousand passenger mile was estimated based on the assumption that average trip distance of BRT passengers was half of the BRT route length.

Overall, figures in the table above indicate that BRT outperforms LRT in all of four operating cost categories. Nevertheless, cautions should be exercised when interpreting these averages. Tennyson [13] has challenged that GAO's study was unevenly biased against LRT – the bus costs were reported too low due to possible inconsistency and errors in the reported data. As with the capital costs reviewed earlier, a wide range of figures exist in each of the four operating costs. The use of alternative measures may give different results on



Bus Versus Rail Implications for Transit-Oriented Development. Figure 1
Trends of operating cost per unlinked passenger trip for bus and rail modes 1998–2007 [16]

Bus Versus Rail Implications for Transit-Oriented Development. Table 5 Maximum line capacities of transit modes

Mode	Vehicle dimensions (L × W m)	Transit unit capacity (Seat + standing spaces)	Minimum headway (s)	Maximum frequency (Transit units per hour)	Line capacity
Standard bus	12.00 × 2.50	75	70–50	51–72	3,800–5,400
Articulated bus	18.00 × 2.5	120	80–60	45–60	5,400–7,200
High-capacity bus (BRT)	22.00 × 2.50	160	30–12	120–300	9,000–30,000
LRT (partially separated ROW)	24.00 × 2.65	3 × 170 = 510 or 2 × 280 = 560	150–75	24–48	12,200–26,900
MRT	21.00 × 3.15	10 × 240 = 2,400	150–120	24–30	67,200–72,000

Source: [17]

the cost performance of bus versus rail. Operating costs for light rail systems vary widely depending upon the system operating environment [14]. For example, operating costs in Buffalo were $67 million dollars a year for an on-street system and $87 million dollar/year for an in-tunnel system [5]. The cost per average weekday boarding on Los Angele's Orange LRT line is $16,743 and $45,762 for the Gold Line Extension [15].

The US National Transit Database reports that, between 1998 and 2007, the operating cost per unlinked trip has increased for all but MRT (Fig. 1) [16].

Capacity of Bus Versus Rail Transit

Bus and rail transit technologies differ in their design capacities. Under different system operational plans, their trunk line capacities may vary significantly. Table 5 provides a reference to the line capacities of standard bus, BRT, LRT, and MRT [17]. The basic capacity of a standard bus serves as a benchmark for line capacity comparisons among these transit modes.

Standard buses can operate in short headways with relatively high frequencies. Unit capacity may vary depending on the bus seating configuration and

comfort standard. On average, standard buses can achieve a line capacity of 3,800–5,400 places per hour. Articulated buses have vehicle capacities approximately 50% greater than standard buses. Operating in slightly longer headways and lower frequencies than standard buses, articulated buses can offer a line capacity between 5,400 and 7,200 places per hour. High-capacity buses are used by many BRT systems in the world. Examples include Sao Paulo and Curitiba, Brazil, and Transmillennio in Bogota, Colombia. They can achieve a line capacity level more than four times the basic bus capacity. Sao Paulo, Curitiba, and Bogota operate high-capacity buses along well-planned bus corridors. Special operating features such as bus convoys and off-board fare collection allow a total throughput of about 300 buses per hour. At such a high frequency, line capacities were reported to achieve 24,000 and 30,000 places per hour in Sao Paulo and Bogota, respectively.

LRT line capacities are close to those attained by high-capacity BRT at 4.2 times that of basic bus capacities. An LRT with fully separated ROW will achieve line capacities higher than figures provided above. MRT systems have a great diversity of features that determine MRT line capacities. For instance, dimensions of metro cars in Paris (15.00 × 2.5 m) are much smaller than in Toronto and Hong Kong (21.00 × 3.23 m). Maximum train lengths also vary, from four cars in Boston to ten or more cars in New York, Tokyo, and San Francisco. In these cities with large-profile systems, line capacities often exceed 70,000 places per hour.

Table 5 provides a reference of transit line capacities under design conditions. In reality, the capacities of these transit systems vary dramatically due to such factors as operational techniques, facility constraints, transit demand, and road conditions. Current debate on BRT-LRT capacity comparisons centers around methods where these constraints are taken into consideration. For example, the communication-based train technology (CBTC) creates very small virtual blocks to allow trains to approach one another in closer intervals. CBTC can increase capacity by 10–15%. Automatic train operation is an operating technology that allows the train to optimize speed, which can increase line capacity by 2–4%. Another factor differentiating the line capacities of bus from train systems is the number of lanes. Typically, BRT travels in a single lane per each direction, whereas rail can follow multiple track lanes. For example, New York has several three- and four-track trunk lines.

Like cost variations, bus and rail transit each offers a wide range of service capacities. Generally speaking, rail transit offers larger capacities than bus transit. In real-world applications, however, it is common to see an overlapping range of capacity offerings by bus and rail transit systems. For instance, BRT in Curitiba achieves far greater higher capacities than the LRT in Buffalo. Vehicle technologies, operation/management efficiencies, and station/street conditions all have significant effects on achievable capacities. Table 6 shows the range of peak-hour capacities suggested by the literature for four aggregated transit modes [18].

Transit Impacts on Property Values

Analyzing rail transit's effects on land use/land development can be built upon the urban location theories, which suggest, in a most succinct form, that transportation defines the urban spatial access pattern

Bus Versus Rail Implications for Transit-Oriented Development. Table 6 Capacity comparison among transit modes

	BUS	BRT	LRT	MRT
Typical peak-hour capacity	1,000–3,000	2,000–10,000	3,000–18,000	13,000–41,000
Ratio to BRT capacity	0.35	1.0	1.65	5.3
Highest observed in the USA or Canada	3,000	11,000	10,000	50,000

Source: [18]

Note: (1) The BRT mode shown here combines those mixed with street traffic and those with dedicated busways. (2) BRT is used for ratio calculation is for consistency with cost comparison shown in previous section.

and accessibility determines the worth of land. In making location decisions, households (or firms) bid for locations by trading housing (and/or land) consumption against commuting costs to the urban center (e.g., the CBD). The closer to the center, the better the access, and the higher the bid rent. Therefore, we would expect a downward sloping accessibility curve from the urban center. Parallel to the accessibility curve is a downward gradient bid-rent curve. Measuring price or rent levels associated with the proximity to rail transit will provide quantified information on the *magnitude* of rail transit's influence on land value and land use.

Research on property/land value impacts of transit has accumulated a large volume of literature. A number of meta-studies have been published [19, 20]. RICS [19] reviewed about 150 references in the topical area. Most of those reviewed are studies from the USA, Canada, the UK, and Europe. Residential properties have been the focus of the existing studies, while commercial, retail, and office properties were also examined.

Table 7 compiles findings of the reviewed studies of transit impacts on property values. Due to differences in methods used in the studies, direct comparisons of the study findings are quite challenging. This entry groups the studies by property types (residential, commercial, or others) and by transit technologies. The focus is on the magnitude of transit proximity effects measured in monetary terms. Due to limited information provided by some of the studies, only part of the reported proximity effects could be converted to 1990 US dollars in comparable units.

Mixed results have been reported on transit proximity premiums associated with apartment rents [21–24]. Results vary mainly depending on the types of transit technologies. Most studies have found positive transit proximity premiums for single-family homes, with a few reporting negative impacts [25–33]. For instance, Armstrong [33] found that single-family home prices were 6.7% higher in communities with a commuter rail station than in communities without. However, a statistically significant property value loss of roughly 20% was found for properties located within 122 m (400 ft) of the right-of-way. Weinberger [34] argues that the presence of transit is a nuisance and may drive down adjacent property values. They cite the noise generated by transit and believe that transit access allows undesirable people easy access to their neighborhoods. Chen et al. [28] tested the nuisance hypothesis in their study of light rail in Portland, Oregon, but found that the benefits to property values attained from proximity to light rail outweighed the negative effects. As shown in Table 7, most studies have identified positive effects of rail transit on nearby properties although some reported negative effects.

LRT tends to have mixed impacts on commercial properties [22, 23, 26, 34], contrasting to mostly positive effects associated with MRT [26, 35–37]. Nelson's [35] study of the Atlanta MARTA heavy rail line showed a negative gradient of \$75 reduced property value per meter from a transit station, indicating a positive benefit associated with access to transit. Weinberger's study suggest positive impacts on commercial property values resulting from proximity to light rail stations, though no specific capitalization rate is provided. The study by Cervero and Duncan shows that in Santa Clara County, commuter rail had a greater impact on commercial property values than the light rail line. Weinstein and Clower's [38] study of the DART light rail system also suggests appreciable effect on commercial properties in the Dallas area from proximity to light rail.

Data on the effects of BRT on property values are quite limited. Rodriguez and Targa [21] estimated that, in Bogota, Columbia, every additional 5 min of walking time to a BRT station reduced rental price by 6.8–9.3%, which translates to a premium of US\$0.05 per m^2 for every meter closer to the station after controlling for the distance to (i.e., the nuisance effect of) the system right-of-way. Also studying Bogota's BRT, Munoz-Raskin [25] confirmed that, in most cases, property values were lower within 5-min distance of the system than those beyond. Cervero and Duncan's [22] study of BRT in Los Angeles found that residential properties near BRT stops sold for less while commercial properties for more. The reason for this negative price effect, according to them, is that the majority of BRT stops are located in redevelopment areas of Los Angeles. In another study looking at how income serves as a determinant in communities' valuing transit, Nelson [10] found that the elevated MARTA heavy rail in Atlanta had positive effects on home values in low-income neighborhoods but negative effects in high-income neighborhoods.

Bus Versus Rail Implications for Transit-Oriented Development. Table 7 Transit impacts on property values

Study	Transit system	Findings	Standardized proximity premium in present US$	Standardized proximity premium in 1990 US$
Apartment (monthly rent in dollars per square meters for every meter closer to the station)				
Rodriguez and Targa (2004) [21]	BRT: Bogota	6.8–9.3% increase for every 5 min walk closer to the station; or in 2002 US$439–653/0.1 km	0.07	0.05
Cervero and Duncan (2002) [22]	LRT: LA County	No significant effects found	0	0
Cervero and Duncan (2002) [23]	LRT: San Diego	East line: within 1/2 mile; 2000 $104,827 more than other locations	0.27	0.21
Benjamin and Sirmans (1996) [24]	MRT: Washington, D.C.	Rents decrease by 2.4–2.6% for each one-tenth mile increase of distance from a metro station. 1992 mean month rent $797	(1.24)	(1.15)
Single-family homes (dollars per home for every meter closer to the station)				
Munoz-Raskin (2006) [25]	BRT: Bogota	In most cases, negative impacts are reported for properties location within 5-min distance to the system		
Landis et al. (1995) [26]	LRT: San Diego Trolley	The typical home sold for 1990 $272 more for every 100 m closer to a light rail station.	2.72	2.72
Landis et al. (1995) [26]	LRT: Sacramento	No effects found	0	0
Landis et al. (1995) [26]	LRT: San Jose	The typical house was worth $197 less for every 100 m it was closer to light rail.	(1.97)	(1.97)
Al-Mosaind et al. (1993) [27]	LRT: Portland MAX, Eastside	The typical house sold for $663 more for every 100 ft nearer a light rail station.	21.74	24.02
Chen et al. (1998) [28]	LRT: Portland MAX, Eastside line	Beginning at a distance of 100 m from the station, each additional meter away from decreases average house price by 1992 $32.20.	32.20	30
Dueker and Bianco (1999) [29]	LRT: Portland MAX, Eastside line	Median house values increase at increasing rates as move toward an LRT station. The largest price difference (1990 $2,300) occurs between the station and 200 ft away.	37.70	37.70
Lewis -Workman and Brod (1997) [30]	LRT: Portland MAX, Eastside line	On average, property values increase by $75 for every 100 ft closer to the station (within the 2,500 ft–5,280 ft radius).	2.25	1.83
Knaap et al. (1996) [31]	LRT: Portland MAX, Westside line	The values of parcels located within ½-mile of the line rise with distance from the lines, but fall with distance from the stations.		
Landis et al. (1995) [26]	MRT: BART	1990 single-family home prices decline by $1–2 per meter of distance from a BART station in Alameda and Contra Costa Counties.	1.50	1.50
Lewis -Workman and Brod (1997) [30]	MRT: BART	Average home prices decline by about $1,578 for every 100 ft further from station.	51.74	43.11

Bus Versus Rail Implications for Transit-Oriented Development. Table 7 (Continued)

Study	Transit system	Findings	Standardized proximity premium in present US$	Standardized proximity premium in 1990 US$
Lewis -Workman and Brod (1997) [30]	MRT: New York City MTA	Average home prices decline by about $2,300 for every 100 ft further from the station areas.	75.41	62.84
Voith (1993) [32]	MRT: Philadelphia SEPTA	Finds a premium for single-family homes with access to rail stations of 7.5–8.0% over the average home value.	7.75%	
Cervero and Duncan (2002) [23]	CRT: San Diego	Price increases by 17% in ½ mile of non-downtown Coaster station	84	63.75
Landis et al. (1995) [26]	CRT: CalTrain	Did not find a significant impact on house values from proximity to a rail station. Houses within 300 m of a CalTrain right-of-way sold at a $51,000 discount.	(170)	(170)
Armstrong (1994) [33]	CRT: Boston MBTA, Fitchburg Line	Single-family residences located in communities that have a rail station have a market value approximately 6.7% greater than those that do not. Also found a property value loss of about 20% for properties located within 400 ft of a commuter or freight rail right-of-way.	6.70%	
Commercial property (dollars per square meter for every meter closer to the station)				
Landis et al. (1995) [26]	LRT: San Diego Trolley	No effect found for commercial impacts	0	0
Weinberger (2001) [34]	LRT: Santa Clara, County Guadalupe line	Commercial space within a ¼-mile of a station received an average of 2.3¢ to 5.0¢ more per square feet than space located more than ¾-mile from a station. Office space sold within a ¼-mile of a station received an average of $4.87 per square feet more per gross building square feet compared to space located more than ¾-mile from a station.	0.36	0.27
Landis et al. (1995) [26]	MRT: BART	Found no effect for commercial property.	0	0
Nelson (1998) [35]	MRT: Atlanta MARTA	Price per square meter falls by $75 for each meter away from transit stations. Price rises by $443 for location within special public interest districts.	75.00	61.07
FTA (2000) [36]	MRT: Washington, D.C.	Price per square foot decreases by about $2.30 for every 1,000 ft further from station.	0.07	0.05
Fejarang et al. (1994) [37]	MRT: Los Angeles	Commercial space within ½-mile of the rail corridor had an additional $31 increase in mean sale price per square feet over the mean sales price of a comparable control group outside of the rail corridor, between 1980 and 1990.	0.39	0.34

One factor that may partly explain the varying empirical findings above is system maturity [12, 14]. Studies conducted on newly constructed transit systems may not capture the positive valuation of transit on property values because housing markets have not had time to react to transit's presence. Transit ridership may serve as an indication of the magnitude that transit can add to property values, since low ridership indicates that transit is not an amenity to be used [14]. Transit technology also matters, with reliability and speed adding value to the system and in turn being capitalized in property values. Unwanted adjacent uses such as freight or industry will also play an important role by reducing neighborhood quality of life [13].

Density for Bus and Rail Transit

A question of general interest is what land-use densities are needed in order to support specific transit operations. The work by Pushkarev and Zupan [39] remains one of the most influential publications on density and transit uses. They plotted with the logarithmic values of population and trip densities on the horizontal and vertical axis, respectively. The log-log graph exhibits virtually a straight line. Specifically, in the New York Region, trips per square mile by MRT increase from 12 at a residential density of 0.8 dwelling units per acre (or du/ac) to more than 60,000 at a density of 200 du/ac. Table 8 shows a typical range of transit supporting densities [39, 40].

Recent studies have confirmed the pattern that Pushkarev and Zupan found 3 decades ago: the closer people live to transit and other services such as shops, the more likely it is that they will utilize the transit and drive less [41, 42]. The study by Frank and Pivo [43] compared travel mode choice among different census tracts with differing levels of employment and population density. They found that transit usage and walking increase as density and land-use mix increase, whereas travel by single-occupancy vehicle (SOV) declines. The relationship between density (employment and population) and mode choice for SOV, transit, and walking displays a nonlinear pattern for both work and shopping trips. Significant modal shifts from SOV to transit and walking occur when employment density increases from 20 to 75 employees per acre or reaches 125 or more employees per acre.

Bus Versus Rail Implications for Transit-Oriented Development. Table 8 Transit supportive densities

Mode	Service	Minimum necessary residential density (dwelling units per acre)	Remarks
Dial-a-bus	Many origins to many destinations	3.5–5	Lower figure if labor costs twice those of taxis; higher if thrice those of taxis
Local bus	Minimum to frequent services; 1/2 mile route spacing; 20–120 buses per day	4–15	Average, varies as a function of downtown size and distance from residential area to downtown
Express bus (BRT) – walk access	Five buses during 2 h peak period	15 Average density over 2 mile^2 tributary area	From 10 to 15 miles away to largest downtowns only
Express bus (BRT) –drive access	Five to ten buses during 2 h peak period	3 Average density over 20 mile^2 tributary area	From 10 to 20 miles away to downtowns larger than 20 million square feet of nonresidential floorspace
Light rail (LRT)	Five-minute headways or better during peak hour.	9 Average density for a corridor of 25–100 mile^2	To downtowns of 20–50 million square feet of nonresidential floorspace
Metro rail (MRT)	Five-minute headways or better during peak hour.	12 Average density for a corridor of 100–150 mile^2	To downtowns larger than 50 million square feet of nonresidential floorspace

Source: From [39, 40]

Population density needs to exceed approximately 13 persons per acre in order to achieve major modal shifts from SOV to non-driving modes for shopping travel.

The Institute of Transportation Engineers in its 1989 publication suggests that, to support bus service with headways of an hour, 4–6 du/ac and 5–8 million square feet of commercial/office space in the corridor is needed; for bus service with 30 min headways, 7–8 du/ac and 8–20 million square feet of commercial/office space is needed; and for light rail and feeder bus service density of 9 du/ac and 35–50 million square feet of commercial/office space is desired [44]. Newman and Kenworthy found that densities of at least 12–16 persons/acre are needed to support urban transit [45]. Similarly, another study found that transit use increases sharply when residential density moves from 7 to 16 du/ac [46]. Levinson [47] found that a relationship between mode choice and density was significant only in densities greater than 10,000 persons per square mile. As much as 93% of the transit demand in Portland, OR can be explained by employment and housing densities [48]. Residential densities of more than 80 du/ac were considered highly supportive, those from 46–80 du/ac medium high, those from 20–45 du/ac medium, 6–19 du/ac medium low, and 0–5 du/ac as low in support of transit [49]. Standard bus service can be maintained at 7 du/ac, and significant transit use increases can occur at 10 du/ac and higher [46, 50]. Lawton has also shown that the higher the density found in an area, the more likely people will walk or take transit and produce less vehicle miles traveled [51].

Some have argued that certain densities of office and other industries can support transit without high-density development [52–54]. Cervero [55] investigated suburban employment densities and found that ride sharing increased by 3.5% for every 5,000 jobs added. Retail and services located near places of employment reduce VMT and prompt workers to utilize transit [56]. Barnes and Davis [57] maintain that commercial land use exerts much more influence on travel choices than do residential densities. Additional work by Cervero has found that suburban employment centers, especially when mixed use is incorporated, prompt the employees to commute via different modes. Furthermore, those living near transit stations are much more likely than others to commute to work by transit [58–60].

Others have emphasized the link between transit usage, car ownership, and centrality instead of transit usage to density [61]. It has been shown that a 10% increase in population centrality (corresponding with higher densities) lowers the chance that a worker drives to work by a margin of 2.1% [62]. Johnson concluded that not only density but density and its spatial relation to the transit stop are both important when evaluating ridership potential [63]. Schimek [64] has argued that, while density matters, its affects are minimal – only providing a 0.7% reduction in auto travel with a 10% rise in density. Another study noted that while density seemed to explain bus usage significantly, it was difficult to properly identify densities, and that destination as well as departure points should be taken into account [65].

Specific densities needed for BRT operation have not been sufficiently identified, although figures for the standard bus-based operations can be borrowed and extrapolated. BRT may perform better in lower-density areas than LRT [66]. In corridors with several medium-density cores but with an overall low-density landscape, BRT's flexibility may make it more suitable than LRT [67].

Transit analysis conducted by the Florida Department of Transportation has ranked densities as to how they may support public transit (Table 9). Residential densities at 80 dwelling units or more per acre are considered highly supportive, whereas

Bus Versus Rail Implications for Transit-Oriented Development. Table 9 Florida DOT's assessment of transit supportive densities

Dwelling units per acre	*Support level*
>80	High
46–80	Medium high
20–45	Medium
6–19	Medium low
0–5	Low

Source: [68]

Bus Versus Rail Implications for Transit-Oriented Development. Figure 2
BRT-based TOD in Curitiba, Brazil

Bus Versus Rail Implications for Transit-Oriented Development. Figure 3
LRT-based TOD node, Mockingbird Station, Texas, USA

less than five dwelling units per acre are not transit supportive [68].

Best Practice of Bus- Versus Rail-Based TOD

Curitiba is the capital city of the Brazilian state of Paraná in Brazil. It presents one of the most successful corridor-type TODs on BRT in the world. Curitiba's BRT system is featured with exclusive rights-of-way, biarticulated buses, tube stations, and land-use zoning coordinated with high-capacity bus corridors (Fig. 2). The system plan is known as the Trinary Model. The model has a two-lane street at the center where the express buses have their exclusive lane. Adjacent to the express lane are two one-way streets moving in the opposite directions. Lots on both sides of the central streets are zoned to develop at high densities. One block from the one-way street on each side of the corridor is a regular two-way street that carries a mix of private vehicle flow and conventional bus services. Five of these roads form a star that converges to the city center. Land farther from the roads is zoned for lower-density developments.

The success of Curitiba's bus-based corridor TOD is shown by a number of key statistics: as of 2008, there were 340 bus lines, 58 km of busways, 1,100 km bus routes, and 26 terminals. Daily the system serves 380,000 passengers by the corridors and 2.4 million by the network. The BRT operates at a less than 1 min headway in the peak hour, peak directions, with an average speed of 30 km/h for the trunk line and 20 km/h for other routes. More than 70% of commuters ride the bus to work.

The Mockingbird Station TOD represents the best practice of TODs implemented around a single node of LRT (Fig. 3). Located four miles north of downtown Dallas, the Mockingbird Station is one of the largest on the Dallas Area Rapid Transit (DART) rail line. Developer Ken Hughes of UC Urban of Dallas initiated and developed the 4-ha project in 2000–2001. Main functions of the TOD site contains 16,536 m^2 of retail, restaurant, and cinema space; 12,727 m^2 of office space, 211 loft apartments; and parking for 1,580 vehicles. The main features of the Mockingbird Station TOD include its combination of adaptive use of historical warehouses with new construction, fine design of streetscape and public arts, and careful organization of pedestrian paths and public as well as private vehicle movement. The success of the Mockingbird Station TOD has proven that a properly conceived TOD can succeed and flourish by serving the adjacent communities, increasing transit use while acting as a catalyst for place making.

Hong Kong's Mass Transit Railway Corporation (MTRC) is one of few successful cases in the world that the rail transit agency is able to fully self-finance system construction and operation by practicing a Hong Kong model of TOD, namely, "Rail + Property" or "R + P" (Fig. 4). Its central idea is to integrate property development with rail operation and construction such that the profit gained from property development pays the operational and capital costs of the rail system. The main working procedures are as follows. First, MTRC studies development potentials in

Bus Versus Rail Implications for Transit-Oriented Development. Figure 4
Tsingyi station: example of Hong Kong's "Rail + Property" TOD model

Bus Versus Rail Implications for Transit-Oriented Development. Table 10 Comparison among major transit modes

	BUS	BRT	LRT	MRT
Capacity: typical peak-hour passengers	1,000–3,000	2,000–10,000	3,000–18,000	13,000–41,000
Capital cost (1990$ per route mile, millions)		$10.24	$26.4	$128.2
Operating cost ($ per vehicle revenue mile)	$3.1	$3.6	$9.3	$6.5
Operating cost ($ per unlinked passenger trip)		$1.51	$2.03	$1.23
Property impacts: apartment (1990$ per square meter for every meter away from transit)		$0.05	$0.3	$1.15
Property impacts: single-family home (1990$ per home for every meter away from transit)			$0–38	$43–62
Minimum density (dwelling units/acre)	4	9	9	12
Ratio to BRT				
Capacity	0.35	1	1.65	5.30
Capital cost		1	2.58	12.52
Operating cost (per vehicle revenue mile)	0.86	1	2.58	1.81
Operating cost (per unlinked trip)		1	1.34	0.82
Minimum density	0.44	1.00	1	1.33

the area of approximately 500-m distance to the proposed stations. It then obtains land development right from the government for the (re)developable properties. The land cost to MTRC (i.e., land premium income to the government) is estimated based on the no-rail scenario. Next, MTRC specifies development plan for the properties in terms of use composition (residential, retail, green space, transportation, etc.), density (i.e., FAR), and other needed facilities. After the government's approval of the plan, MTRC develops the rail system and the station area in partnership with developers. Because of rail transit availability, property value increases. MTRC then sells properties to individuals or firms, sharing the profits with developers and the government. The MTRC's earnings will be used for maintenance and expansion of rail services as well as other expenses or investments.

MTRC's R + P model proves to offer an all-win solution, at least in the scope of MTRC's services. MTRC benefits from guaranteed funds for service delivery and expansion. To the community, ordinary citizens enjoy high-quality rail services while the share of household expenditure in transportation remains low (9%) [69]. To the developer, MTRC plays a coordinator role, helping reduce start-up costs. The government is a big winner as well. Since 2000 when MTRC went public, the R + P practice has enabled MTRC to operate high-quality rail services without asking subsidy from the government. Furthermore, the Hong Kong government has received a profit (net initial equity contribution) of over HK$103 billion from its 76% MTRC shares.

Conclusions

Table 10 summarizes modal characteristics of bus- and rail-based transit systems. Main categories of features for comparison include capacity, cost (capital and operating), land-use impacts, and transit supportive densities. For easy reference, their attributes are normalized by using BRT as the main reference.

The comparisons depicted above indicate that, on average, BRT has the potential to outperform LRT in providing a moderate to high level of service capacity at a moderate level of capital and operating costs in neighborhoods with moderate population and job densities. MRT, although most expensive to build, can

achieve over five times the capacity of BRT or LRT and has demonstrated the largest positive impacts on property values in the vicinity of rail stations.

The reviews provided in this entry on the comparative costs, capacities, and land-use impacts of various rapid transit technologies suggest that no simple answer exists to the question. Perhaps no single form of transit will fit all market needs of a community. Each transit technology is efficient when it is in the right place serving the right market. It is more likely the case that all forms of transit systems coexist, each serving a particular market niche. The key is to propose context-sensitive TODs for integrated development transit with land use.

Future Directions

Current TOD practices and studies have largely focused on nodal TODs, that is, the stand-alone TODs around individual bus stops or train stations. However, many community objectives, for instance, affordable housing provision, job-housing balance, and congestion relief, cannot be well addressed at the individual TOD basis. From a traveler's perspective, whether she/he uses transit depends not only on what the origin can offer but also on what amenities the destination provides. Hence, an important direction for future study is Corridor TOD, which formulates development and implementation strategies at the corridor scale along bus or rail transit routes.

Another future direction is TOD-based value capture for transit financing. Existing TOD initiatives are mostly concerned with physical planning and design of TODs as well as legal and political barriers to TOD implementation. There are successful examples as mentioned above on TOD-based value capturing through integrated transit-land development. How the successful experience can be transferred to cities and countries with different legal, institutional, and financial settings remains a challenge and warrants future research.

Furthermore, the current urban TOD practice can be expanded to other modes of transportation for intercity travel, for example, air, ferry, and high-speed rail. Stations and terminus for intercity transportation typically have more complex traffic operations than those of intracity transit. A new trend is to develop the station or terminal areas as multifunctional places rather than traditionally as single-function transportation hubs. TOD principles can be applied to these cross-region modes, while their technological complexities require specific consideration.

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